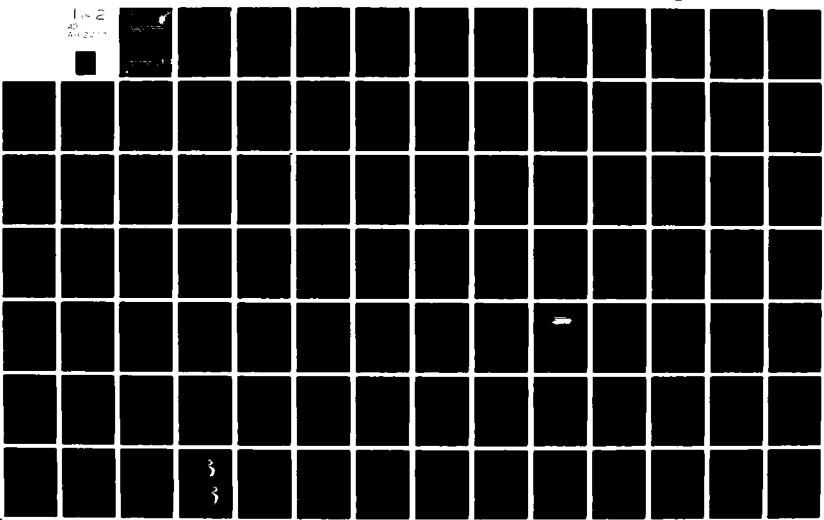
AD-A102 207 LOWELL UNIV MA F/G 20/3
ANALYSIS AND COMPUTER STUDIES FOR MAGNETOSTATIC SURFACE WAVE TR--ETC(U)
MAY 81 J I WEINBERG F19628-80-C-0029
UNCLASSIFIED RADC-TR-81-96 NL

1 of 2
AD
A102207



LEVEL II

RADC-TR-81-96
Interim Report
May 1981

AD A102207

ANALYSIS AND COMPUTER STUDIES FOR MAGNETOSTATIC SURFACE WAVE TRANSDUCERS

University of Lowell

Jacob I. Weinberg

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

This report has been reviewed by the RADC Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RADC-TR-81-96 has been reviewed and is approved for publication.

APPROVED: James C. Sethares

JAMES C. SETHARES
Project Engineer

APPROVED: Allan C. Schell

ALLAN C. SCHELL
Chief, Electromagnetic Sciences Division

FOR THE COMMANDER: John P. Huss

JOHN P. HUSS
Acting Chief, Plans Office

If your address has changed or if you wish to be removed from the RADC mailing list, or if the addressee is no longer employed by your organization, please notify RADC (EEAC) Hanscom AFB MA 01731. This will assist us in maintaining a current mailing list.

Do not return this copy. Retain or destroy.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RADC-TR-81-96	2. GOVT ACCESSION NO. AD-A102207	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANALYSIS AND COMPUTER STUDIES FOR MAGNETOSTATIC SURFACE WAVE TRANSDUCERS		5. TYPE OF REPORT & PERIOD COVERED Interim Report
		6. PERFORMING ORG. REPORT NUMBER N/A
7. AUTHOR(s) Jacob I. Weinberg		8. CONTRACT OR GRANT NUMBER(s) F19628-80-C-0029
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Lowell 450 Aiken Street Lowell MA 01854		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2305J528
11. CONTROLLING OFFICE NAME AND ADDRESS Deputy for Electronic Technology (RADC/EEAC) Hanscom AFB MA 01731		12. REPORT DATE May 1981
		13. NUMBER OF PAGES 106
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

RADC Project Engineer: James C. Sethares (EEAC)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Magnetostatic Waves
Microwave Magnetics
Yttrium Iron Garnet
Ferrimagnetic Films

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes results of work on magnetostatic surface wave transducers. Presented are the results for the dispersion relation, radiation resistance and insertion loss for magnetostatic surface wave transducers which may include a gap and apodization. Independent conductors as well as normal modes are considered. Also presented are the results for the dispersion relation for surface waves for a variety of alignments of the externally applied magnetic biasing field. Com-

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

312

puterized graphs of the results are presented here. Comparisons are made with results obtained from the analysis of the microstrip model which is also presented.

Accession For	
NTIS GRA&I	X
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	

Table of Contents

Magnetostatic Surface Wave Transducers

Introduction

The purpose of this report is to summarize the results of the work on magnetostatic surface wave transducers under contract number F 19628-80-C-0029 from the U.S. Air Force ESD RADC EEA at Hanscom AFB, Ma.

To be presented are the results for the dispersion relation, radiation resistance, radiation reactance and insertion loss for magnetostatic surface wave transducers which may include a gap and apodization. Independent conductors as well as normal modes are considered. Also presented are the results for the dispersion relation for surface waves for a variety of alignments of the externally applied magnetic biasing field.

Computerized results including computerized graphs of the results are presented here. Comparisons are made with results obtained from the analysis of the microstrip model which is also here presented.

Basic Theory

The basic theory leading to the dispersion relation, magnetostatic wave power, radiation resistance, radiation reactance and insertion loss for surface waves when the applied magnetic biasing field is in the direction of the Z axis (see Figure 1) has been previously detailed [1],[2],[6],[8],[12]. This theory will here be outlined.

We start with Maxwells equations

$$\nabla \times \bar{H} = \frac{\partial \bar{D}}{\partial t} \quad ; \quad \nabla \cdot \bar{B} = 0$$
$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \quad ; \quad \nabla \cdot \bar{D} = 0 \qquad (1)$$

and the constitutive relations in each of the four regions

$$\bar{B} = \mu_o (\bar{H} + \bar{M})$$
$$\bar{D} = \varepsilon \bar{E} \qquad (2)$$

where $\bar{M}$ is taken as zero in all regions except the YIG region. We utilize the gyromagnetic relation in the YIG region

$$\frac{\partial \bar{M}}{\partial t} = -\gamma \bar{M} \times \bar{H} \qquad (3)$$

and retain only first order terms.

We assume the time dependence of all physical quantities to be $e^{j\omega t}$. We also take the magnetostatic approximation

$$H_z = E_x = E_y = 0$$
$$\omega \varepsilon E_z = 0 \qquad (4)$$

and no variation of any physical quantity in the z direction.

In particular, we obtain

$$\frac{\partial E_z}{\partial y} = - j \omega B_x$$
$$\frac{\partial E_z}{\partial x} = + j \omega B_y \tag{5}$$

and

$$B_x = \mu_o H_x$$
$$B_y = \mu_o H_y \tag{6}$$

in all regions except the YIG, while

$$\begin{pmatrix} B_x \\ B_y \end{pmatrix} = \mu_o \begin{pmatrix} \mu_{11} & -j\mu_{12} \\ j\mu_{21} & \mu_{22} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix} \tag{7}$$

in the YIG region where

$$\mu_{11} = \mu_{22} = 1 - \frac{\Omega_H}{\Omega^2 - \Omega_H^2}$$

$$\mu_{21} = \mu_{12} = \frac{\Omega}{\Omega^2 - \Omega_H^2}$$

$$\Omega = \frac{f/\gamma}{4\pi M_o} \tag{8}$$

$$\Omega_H = \frac{H_o}{4\pi M_o}$$

$$\gamma = 2.8 \text{ mhz/oe} \quad ; \quad 4\pi M_o = 1750 \text{ oe}$$

$$f = \omega/2\pi$$

Solutions are sought which satisfy continuity conditions for H_x and B_y at each region junction and satisfy B_y=o at the ground planes. At y=g the condition to be satisfied is that H_x is discontinuous by the surface current density J(x).

We thus assume a solution form of a potential function

$$\psi = F(y)\ e^{j(\omega t - Kx)} \tag{9}$$

where

$$H_x = \frac{\partial\psi}{\partial x} \quad ; \quad H_y = \frac{\partial\psi}{\partial y} \tag{10}$$

In the non YIG regions we find the form of F(y) to be

$$F(y) = A_i\ e^{|k|y} + B_i\ e^{-|k|y} \qquad i=1,3,4 \tag{11}$$

while, in the YIG region

$$F(y) = A_2\ e^{\beta|k|y} + B_2\ e^{-\beta|k|y} \tag{12}$$

where

$$\beta^2 = \mu_{11}/\mu_{22} \tag{13}$$

so that the basic equations (1) - (8) are satisfied. One can see that these solutions consist of waves propogating in the X direction. We carry β along in the analysis even though its value is unity by (13) and (8) because of comparisons to be made later with the analysis for a general direction of the applied biasing field.

The attempt to satisfy the continuity and boundary conditions results first in the requirement to solve[2]

$$F_T(K) = 0 \tag{14}$$

where

$$F_T(K)=\frac{(\coth|K|t_1-1)}{2}\left[(1+\alpha_2)e^{-2\beta|k|d}+(1-\alpha_1)T\right]e^{-|K|g}-\frac{(\coth|K|t_1+1)}{2}$$

$$\left[(1-\alpha_2)e^{-2\beta|K|d}+(1+\alpha_1)T\right]e^{|K|g} \tag{15}$$

and

$$\alpha_1 = \mu_{22}\,\beta + \frac{|K|}{K}\,\mu_{12}$$

$$\alpha_2 = \mu_{22}\,\beta - \frac{|K|}{K}\,\mu_{12} \tag{16}$$

$$T = \frac{(\alpha_2+\tanh\,|K|\ell)}{(\alpha_1-\tanh\,|K|\ell)}$$

Equation (14), a transcendental equation for K as a function of f, is the dispersion relation. Numerical techniques are required for its solution. Two solution curves of K vs. f result; in one solution K is always positive and in the other solution K is always negative. This results in two solution waves which are in opposite directions. Denoting

$$\frac{|K|}{K} = S \tag{17}$$

and the solution values of K by K_S, S=-1, 1, we have that the two dispersion relation curves are obtained by solving (14) with (16) for S=-1 and S=1.

Equation (14) can also be written as[8]

$$e^{-2|K|\tau} = \frac{(1-\alpha_2)e^{-2\beta|K|d} + (1+\alpha_1)T}{(1+\alpha_2)e^{-2\beta|K|d} + (1-\alpha_1)T} \tag{18}$$

where

$$\tau = t_1 + g \tag{19}$$

which shows that the effects of material thickness t_1 and g enter the dispersion relation only in combination.

Another useful way of writing the dispersion relation is[13]

$$e^{-2\beta|K|d} = \frac{(\alpha_1+\tanh|K|\tau)(\alpha_2+\tanh|K|\ell)}{(\alpha_2-\tanh|K|\tau)(\alpha_1-\tanh|K|\ell)} \tag{20}$$

The bandwidth of frequencies for which the solution of (14) can be obtained is given by[5]

$$\gamma\sqrt{H_o(H_o+4\pi M_o)} < f < \gamma\ (H_o+2\pi M_o) \tag{21}$$

Having the dispersion relation curves we can find the group delay

$$V_g = \frac{\partial\omega}{\partial K} \tag{22}$$

for each of the two solution curves.

After equation (14) has been solved we can find all quantities of physical interest for each of the two solutions of (14) [2]. The magnetostatic wave power is then obtained from [2],[3]

$$P^{(s)} = \frac{1}{2} \int_{-(\ell+d)}^{\tau} E_z^{(s)}\ \overline{H_y^{(s)}}\ dy \qquad s=-1,1 \tag{23}$$

where E_z is related to H_y, and H_x in the YIG region, by equations (5) with (6) or (7).

The expression for power is found to be [2]

$$P^{(s)} = \frac{-s\,\omega\,\mu_o}{2\,K_s^2}\, A_s\, G_s^2 \qquad s=-1,1 \tag{24}$$

where

$$G_s = \frac{e^{-\beta|K_s|d}\,|\tilde{J}_1(K_s)|}{\left|\frac{\partial}{\partial K} F_T(K)\right|_{K=K_s}} \qquad s=-1,1 \tag{25}$$

$$A_s = \frac{(T_s+1)^2}{\cosh^2|K_s|\ell}\left(\frac{\sinh 2|K_s|\ell}{4} - \frac{|K_s|\ell}{2}\right) + \frac{(U_s\, e^{|K_s|g} - V_s\, e^{-|K_s|g})^2}{4\sinh^2 |K_s|t_1}\left(\frac{\sinh 2|K_s|t_1}{4} - \frac{|K_s|t_1}{2}\right)$$

$$+ \frac{1}{4}\left[\frac{U_s^2}{2}(e^{2|K_s|g}-1) - \frac{V_s^2}{2}(e^{-2|K_s|g}-1) - 2\,U_s\,V_s\,|K_s|g\right] \tag{26}$$

$$+ \left[\frac{\alpha_1^{(s)}}{2}T_s^2\,(e^{2\beta|K_s|d}-1) - \frac{\alpha_2^{(s)}}{2}(e^{-2\beta|K_s|d}-1) - 2\,\beta^2\,|K_s|T_s d\,\mu_{22}\right] \qquad s=-1,1$$

$$U_s = (1-\alpha_2^{(s)})e^{-\beta|K_s|d} + (1+\alpha_1^{(s)})T_s\, e^{\beta|K_s|d}$$

$$V_s = (1+\alpha_2^{(s)})e^{-\beta|K_s|d} + (1-\alpha_1^{(s)})T_s\, e^{\beta|K_s|d}$$

$$s=-1,1 \tag{27}$$

$$\alpha_1^{(s)} = \alpha_1(K_s)\ ,\ \alpha_2^{(s)} = \alpha_2(K_s)\ ,\ T_s = T(K_s)$$

For independent conductors [4],[12]

$$\tilde{J}_1(K_s) = \sum_{i=1}^{N} \operatorname{sinc}\frac{a_i K_s}{2\pi}\, \eta^i \sqrt{\ell_{1i}}\; e^{-j\,K_s\,p_i\,i} \qquad s=-1,1 \tag{28}$$

For the non-apodized independent conductor case, (28) can be written as [13], with $I_o=1$,

$$\tilde{J}_1(K_s) = I_o \operatorname{sinc} \frac{a K_s}{2\pi} \frac{1-\eta^N e^{jK_s pN}}{1-\eta\, e^{jK_s p}} \tag{29}$$

For a truncated array of normal modes we have for the fundamental mode (n=1)

$$\tilde{J}_1(K_s) = \sum_{i=1}^{N} \operatorname{sinc}\frac{2 a_i}{p_i(3-\eta)} \operatorname{sinc}\left[\frac{K_s p_i}{2\pi} - \frac{3+\eta}{4}\right] \eta_i \sqrt{\ell_{1i}}\, e^{-jK_s p_i i} \tag{30}$$

$$s=-1,1$$

where ℓ_{1i}, a_i, p_i $i=1,2,\ldots,N$ are the conducting strip lengths, conducting strip widths and center to center spacings, respectively, to account for apodization. N is the number of conducting strips and $\eta=-1$ for a meander line and $\eta=1$ for a grating.

The definition

$$\operatorname{sinc} X = \frac{\sin \pi X}{\pi X} \tag{31}$$

is employed in the above.

In the free space case, $t_1=\infty$ and $\ell=\infty$, the dispersion relation is

$$e^{-2\beta|K|d} = \frac{(\alpha_1+1)(\alpha_2+1)}{(\alpha_2-1)(\alpha_1-1)} \tag{32}$$

from (20). The expression for A_s in the power is

$$A_s = \frac{(T_s+1)^2}{2} + \left[\frac{\alpha_1^{(s)}}{2} T_s^2 \left(e^{2\beta|K_s|d}-1\right) - \frac{\alpha_2^{(s)}}{2} \left(e^{-2\beta|K_s|d}-1\right) - 2\beta^2 T_s \mu_{22} d|K_s|\right] + \frac{V_s^2}{8} \tag{33}$$

The radiation resistance is then obtained from

$$R^{(s)} = \frac{4\,|P^{(s)}|}{(1-\eta)+(1+\eta)N^2} \qquad s=-1,1 \qquad (34)$$

In the above it is typical that the amplitudes for the wave corresponding to s=-1 is greater than the amplitudes for the wave corresponding to s=+1. Thus the s=-1 wave is the stronger of the two and is denoted by the + wave and the s=1 wave is denoted by the - wave.

The total radiation resistance is then

$$R_m = R^+ + R^- \qquad (35)$$

The radiation reactance contributes meaningfully for surface waves. It is to be obtained from

$$X_m(f) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{R_m(f')}{f' - f}\, df' \qquad (36)$$

Although this integral contains infinite limits and an apparent singularity it can be computed accurately by numerical techniques [6],[7]. We thus find the radiation reactance from the numerical values of the previously obtained radiation resistance.

The combination of radiation resistance and radiation reactance then results in the complex radiation impedance.

We can now find insertion loss from the radiation resistance, radiation reactance and by including source resistance, conduction loss, matching reactance and propagation loss. We obtain [8]

$$IL^{(s)} = 20\,\log_{10} \frac{4R^{(s)}\,R_g}{(R_g+R_m+R_L)^2+(X_m+X_L)^2} - \frac{76.4\,\Delta H\ \Delta r}{\partial\omega/\partial K} \qquad s=-1,1 \quad (37)$$

where R_g is the source resistance, R_L is the conduction loss and X_L is a series matching reactance. ΔH is a linewidth representing material loss and Δr is a propagation distance.

This completes the basic theory for magnetostatic surface wave transducers.

Microstrip Model

In the microstrip model [9],[11] insertion loss is calculated from input resistance and inputt reactance of a lossy shorted section of microstrip line and microstrip propagation constants. Apodization is not taken into account in this theory. The conducting strip dimensions ℓ_1, a and p are thus the same for all strips.

First consider one conducting strip. Here

$$\tilde{J}(K_s) = \operatorname{sinc} \frac{a\,K_s}{2\pi}\ \eta\sqrt{\ell_1}\ e^{-jK_s p} \tag{38}$$

from the independent conductor model, (28).

For N strips we then have, multiplying by an array factor,

$$R^{(s)} = \frac{4|P^{(s)}|}{(1-\eta)+(1+\eta)} \left(\frac{\sin \frac{NK_s p}{2}}{\sin \frac{K_s p}{2}} \right)^2 \qquad s=-1,1 \tag{39}$$

for $\eta=1$, and

$$R^{(s)} = \frac{4|P^{(s)}|}{(1-\eta)+(1+\eta)} \left(\frac{\sin \frac{NK_s p}{2}}{\cos \frac{K_s p}{2}} \right)^2 \qquad s=-1,1 \tag{40}$$

for $\eta=-1$ and N even where, $P^{(s)}$ is computed for N=1 in (39) and (40).

From the above and (35) and (36) we have R^+, R^-, R_m and X_m.

To obtain insertion loss we first define

$$\overline{R^{(s)}} = \frac{R^{(s)}}{\ell_{1/2}} \qquad s=-1,1$$

$$\overline{R_m} = \frac{R_m}{\ell_{1/2}} \qquad (41)$$

$$\overline{X_m} = \frac{X_m}{\ell_{1/2}}$$

Given characteristic impedance Z_{c1}, propagation constant $\overline{\beta}_c$, conduction loss constant α_{cK} and conductivity σ, we have, for N=1

$$\overline{\beta_1} = \overline{\beta}_c f$$

$$\overline{\alpha_R} = \frac{\overline{R}_m}{2Z_{c1}} \qquad (42)$$

$$\overline{\alpha}_c = \alpha_{cK} \sqrt{f/\sigma} \Big/ Z_{c1}\, a$$

where $\overline{\alpha}_R$ and $\overline{\alpha}_c$ represent radiation attenuation loss and conduction attenuation loss, respectively.

For one or more conducting strips, $N \geq 1$, we now have

$$Z_c = Z_{c1}/N$$

$$\alpha_R = \overline{\alpha}_R/N \qquad \eta=1 \qquad (43)$$

$$\overline{\beta} = \overline{\beta}_1$$

$$\alpha_c = \overline{\alpha}_c$$

and

$$Z_c = Z_{c1}$$

$$\alpha_R = \bar{\alpha}_R/N \qquad \eta=-1 \text{ and } N \text{ even} \tag{44}$$

$$\bar{\beta} = \bar{\beta}_1 N$$

$$\alpha_c = \bar{\alpha}_c N$$

Total attenuation loss is then

$$\alpha = \alpha_R + \alpha_c \tag{45}$$

Then compute

$$R_{in} = \frac{Z_c \tanh 2\alpha \ell_1}{1+\cos 2\bar{\beta}\ell_1 \operatorname{sech} 2\alpha \ell_1}$$

$$X_{in} = \frac{Z_c \sin 2\bar{\beta}\ell_1 \operatorname{sech} 2\alpha \ell_1}{1+\cos 2\bar{\beta}\ell_1 \operatorname{sech} 2\alpha \ell_1} \tag{46}$$

$$Z_{in} = \sqrt{R_{in}^2 + X_{in}^2}$$

where R_{in}, X_{in} and Z_{in} are input resistance, input reactance and the magnitude of the input impedance, respectively. With

$$R_{i,m}^{(s)} = R_{in} \frac{\overline{R^{(s)}}/Z_c}{\alpha_c + \bar{R}_m / Z_c} \qquad s=-1,1$$

$$R_{i,m} = R_{i,m}^{+} + R_{i,m}^{-} \tag{47}$$

insertion loss can be expressed as

$$IL^{(s)} = 20 \log_{10} \frac{4 R_i R_{i,m}^{(s)}}{(R_i+R_{in})^2 + X_{in}^2} - \frac{76.4 \;\Delta H \;\Lambda r}{\partial\omega/\partial K} \qquad s=-1,1 \tag{48}$$

where R_i is the source impedence.

Insertion loss can also be written as

$$IL^{(s)} = 20 \log_{10} \frac{4 R_i R_{i,m}^{(s)}}{(R_i+R_c+R_{i,m})^2+(X_{i,m}+X_\ell)^2} - \frac{76.4 \Delta H \Delta r}{\partial\omega/\partial K} \quad s=-1,1 \quad (49)$$

where

$$R_c = R_{in} \frac{\alpha_c}{\alpha_c+\overline{R}_m/Z_c}$$

$$X_\ell = X_{in} \frac{\overline{\beta}}{\overline{\beta}+ \overline{X}_m/Z_c} \qquad (50)$$

$$X_{i,m} = X_{in} \frac{\overline{X}_m/Z_c}{\overline{\beta}+\overline{X}_m/Z_c}$$

This completes the theory for the microstrip model.

<u>Complex Impedance-Free Space Case</u>

We here indicate the computation of the magnetic wave power P when all physical quantities are determined by combining the two solutions present. We shall only consider the free space case ($\ell=t_1=\infty$) and the case of no gap present (g=o). Since β=1 in the basic theory, we will eliminate it from the equations.

We write

$$\alpha_1^{(s)} = \mu_{22} + S \mu_{12}$$

$$\alpha_2^{(s)} = \mu_{22} - S \mu_{12} \qquad s=-1,1 \qquad (51)$$

$$T_S = \frac{\alpha_2^{(s)} + 1}{\alpha_1^{(s)}-1}$$

and define

$$a_s = \frac{1}{T_s}$$
$$\bar{G}_s = \frac{G_s}{a_s} \tag{52}$$

The magnetic wave power defined as

$$P = \frac{1}{2} \int_{-\infty}^{\infty} E_z \bar{H}_y \, dy \tag{53}$$

is now

$$P = \frac{1}{2} \left[\int_{-\infty}^{-d} E_{z1} \bar{H}_{y1} \, dy + \int_{-d}^{o} E_{z2} \bar{H}_{y2} \, dy + \int_{o}^{\infty} E_{z4} \bar{H}_{y4} \, dy \right] \tag{54}$$

Considering both solutions we have

$$P=\frac{1}{2} \left[\int_{-\infty}^{d} (E_{z1}^{(-1)}+E_{z1}^{(1)}) (\overline{H_{y1}^{(-1)}}+\overline{H_{y1}^{(1)}})dy+ \int_{-d}^{o} (E_{z2}^{(-1)}+E_{z2}^{(1)}) (\overline{H_{y2}^{(-1)}}+\overline{H_{y2}^{(1)}})dy+ \right.$$
$$\left. \int_{o}^{\infty} (E_{z4}^{(-1)}+E_{z4}^{(1)}) (\overline{H_{y4}^{(-1)}}+\overline{H_{y4}^{(1)}})dy \right] \tag{55}$$

Employing (5) with (6) or (7) together with (9)-(12) indicates the form of (55) is

$$P = \frac{1}{2} \left\{ \int_{-\infty}^{-d} \left[E_{-1}(y)e^{-jK_{-1}x} + E_1(y)e^{-jK_1x}\right]\left[H_{y-1}(y)e^{jK_{-1}x} + H_{y1}(y)e^{jK_1x}\right] dy \right.$$
$$+ \int_{-d}^{o} \left[E_{-2}(y)e^{-jK_{-1}x} + E_2(y)e^{-jK_1x}\right]\left[H_{y-2}(y)e^{jK_{-1}x} + H_{y2}(y)e^{jK_1x}\right] dy$$
$$\left. + \int_{o}^{\infty} \left[E_{-4}(y)e^{-jK_{-1}x} + E_4(y)e^{-jK_1x}\right]\left[H_{y-4}(y)e^{jK_{-1}x} + H_{y4}(y)e^{jK_1x}\right] dy \right\} \tag{56}$$

and, upon insertion of the appropriate solution functions in (55) and the performance of the indicated integrations we obtain the result

$$P = \frac{-\omega\mu_o}{2} \left\{ M_9 + M_8 \cos (K_1 - K_{-1})x + j\, M_7 \sin (K_1 - K_{-1})x \right\} \tag{57}$$

where

$$M_9 = \sum_{s=-1}^{1} \frac{s\, \overline{G}_s^{\,2}}{2\, K_s^{\,2}} \Big[(1+a_s)^2 + \alpha_1^{(s)} \left(e^{2|K_s|d} - 1\right) - \alpha_2^{(s)} \left(e^{-2|K_s|d} - 1\right) a_s^2$$

$$-2|K_s| a_s \left(\alpha_1^{(s)} + \alpha_2^{(s)}\right) d + \left(a_s\, \alpha_2^{(s)}\, e^{-|K_s|d} - \alpha_1^{(s)}\, e^{|K_s|d}\right)^2 \Big] \tag{58}$$

$$M_8 = \frac{\overline{G}_1\, \overline{G}_{-1}}{-K_1\, K_{-1}} \Big\{ \frac{(K_1+K_{-1})}{(K_1-K_{-1})} (1+a_{-1})(1+a_1) + \alpha_2^{(1)} a_1 \left(e^{-(K_1+K_{-1})d} - 1\right) - \alpha_1^{(1)} a_{-1} \left(e^{(K_1+K_{-1})d} - 1\right)$$

$$+ \frac{\left(e^{(K_1-K_{-1})d} - 1\right)\left(\alpha_1^{(-1)} K_1 + \alpha_1^{(1)} K_{-1}\right) - a_{-1} a_1 \left(e^{-(K_1-K_{-1})d} - 1\right)\left(\alpha_2^{(-1)} K_1 + \alpha_2^{(1)} K_{-1}\right)}{(K_1-K_{-1})} \tag{59}$$

$$+ \frac{(K_1+K_{-1})}{(K_1-K_{-1})} \left(a_{-1}\, \alpha_2^{(-1)} e^{K_{-1}d} - \alpha_1^{(-1)}\, e^{-K_{-1}d}\right)\left(a_1\, \alpha_2^{(1)}\, e^{-K_1 d} - \alpha_1^{(1)} e^{K_1 d}\right) \Big\}$$

$$M_7 = \frac{\overline{G}_1\, \overline{G}_{-1}}{-K_1\, K_{-1}} \Big\{ (1+a_{-1})(1+a_1) + \left(a_{-1}\, \alpha_2^{(-1)}\, e^{K_{-1}d} - \alpha_1^{(-1)} e^{-K_{-1}d}\right)\left(a_1\, \alpha_2^{(1)}\, e^{-K_1 d} - \alpha_1^{(1)} e^{K_1 d}\right)$$

$$+ \frac{(K_1-K_{-1})}{(K_1+K_{-1})} \left[\alpha_2^{(1)}\, a_1 \left(e^{-(K_1+K_{-1})d} - 1\right) - \alpha_1^{(1)}\, a_{-1} \left(e^{(K_1+K_{-1})d} - 1\right) \right] \tag{60}$$

$$+ \frac{\left(e^{(K_1-K_{-1})d} - 1\right)\left(\alpha_1^{(-1)}\, K_1 - \alpha_1^{(1)} K_{-1}\right) - a_{-1} a_1 \left(e^{-(K_1-K_{-1})d} - 1\right)\left(\alpha_2^{(-1)} K_1 - \alpha_2^{(1)} K_{-1}\right)}{(K_1-K_{-1})} \Big\}$$

Note that (57) is of the form

$$P = P_R + j\, P_I \tag{61}$$

where

$$P_R = \frac{-\omega\mu_o}{2}\left[M_9 + M_8 \cos\ (K_1 - K_{-1})x\right]$$
$$P_I = \frac{-\omega\mu_o}{2}\ M_7 \sin\ (K_1 - K_{-1})x \qquad (62)$$

The results obtained reduce to that obtained earlier in (24),(25) and (33) when the two solutions are considered separately and (50) and the dispersion relation (31) is utilized. In this case the only terms present in (57) are the two terms in M_9, one for each value of S, from (58).

In general, the complex impedance is taken as

$$Z = \frac{4\ P}{(1-\eta)+(1+\eta)N^2} \qquad (63)$$

similar to (34) and has real and imaginary parts. The spatial average of this generalized impedance gives the radiation resistance, while the spatially dependent part gives rise to resistance and reactance terms related to the width of the transducer in the x direction. These terms are assumed to be of second order and have not been incorporated into the present model.

Generalized Dispersion Relation

In this section we obtain the dispersion relation for surface waves when the biasing field is not restricted to be parallel to the Z axis (see Figure 1).

In the YIG region the components of the permeability tensor (7) are now given by [10]

$$\mu_{11} = 1 + \frac{\gamma^2 H_o (4\pi M_o)(\sin^2\theta \ \sin^2\phi + \cos^2\theta)}{\gamma^2 \ H^2 - f^2}$$

$$\mu_{22} = 1 + \frac{\gamma^2 H_o (4\pi M_o) \ \sin^2\theta}{\gamma^2 \ H^2 - f^2} \tag{64}$$

$$-j\mu_{12} = \frac{j \ \gamma(4\pi M_o)\sin\theta \ (f \ \sin\theta + j\gamma H_o \ \cos\phi \ \cos\theta \ )}{\gamma^2 \ H^2 - f^2}$$

$$j\mu_{21} = \frac{-j \ \gamma(4\pi M_o)\sin\theta \ (f \ \sin\theta - j\gamma H_o \ \cos\phi \ \cos\theta)}{\gamma^2 \ H^2 - f^2}$$

These relations reduce to those given by (8) for the case of the biasing field lying along the z axis; θ=90° and ϕ=90°.

The satisfaction of (1)-(3) yields solutions as in (8), the expression in the YIG region being modified to

$$F(y) = e^{-jKby}(A_2 \ e^{\beta|K|y} + B_2 \ e^{-\beta|K|y}) \tag{65}$$

instead of (12). Here

$$\beta^2 = \frac{(\mu_{21}-\mu_{12})^2 + 4\mu_{11} \ \mu_{22}}{4\mu_{22}^{\ 2}} > o \tag{66}$$

instead of (13), and

$$b = \frac{-j(\mu_{21} - \mu_{12})}{2 \ \mu_{22}} \tag{67}$$

We note that b is real and that the term containing b indicates that there is an additional propagation component in the y direction. For the standard surface wave case of θ=90° and ϕ=90° we note that (65) and (66) reduce to (12) and (13) with b=o.

The dispersion relation is obtained by satisfying the boundary and continuity conditions as before. With

$$\alpha_1 = \beta\, \mu_{22} - j\, \frac{|K|}{K}\, (j\, \mu_{21} + b\, \mu_{22})$$

$$\alpha_2 = \beta\, \mu_{22} + j\, \frac{|K|}{K}\, (j\, \mu_{21} + b\, \mu_{22}) \tag{68}$$

the dispersion relation, for the case of g=o, is

$$e^{2\beta|K|d} = \frac{(\alpha_2 - \tanh\, |K|t_1)(\alpha_1 - \tanh\, |K|\ell)}{(\alpha_2 + \tanh\, |K|\ell)\ (\alpha_1 + \tanh\, |K|t_1)} \tag{69}$$

Again, for the case of θ=90° and ϕ=90° equations (68) coincide with (16) and (69) is then the same as (20).

Thus (69) with (68), (67), (66) and (64) give the dispersion relation for surface waves with the orientation of the biasing field kept arbitrary.

COMPUTER PROGRAMS

A. Basic Theory

A computer program which incorporates the results of the basic theory has been made operational on the CDC 6600 at Hanscom AFB, Ma. The program produces plots of the various physical quantities as functions of frequency. There are plots of wave number, group delay, radiation resistance and insertion loss for each of the two solution waves. There are also plots of the normalized dispersion for the + wave, total radiation resistance and the corresponding total radiation reactance. The program also provides for print out of these quantities.

The program is designed for flexibility in that independent conductors as well as a truncated infinite array of normal modes can be accomodated. The case of uniform conducting strips can be handled as well as apodization in strip length, strip width and/or center to center spacing. In addition, the program automatically computes the relevant frequency range by utilizing (21).

There now follows a detailed description of the input cards to the program which shows how to use the features described above.

Card 1 - H_o, t_1, d, g, ℓ, N, η

These seven quantities are here supplied, separated by commas. All lengths are in meters. Columns 1-72 may be used.

Card 2 - first ℓ_1, $\Delta\ell_1$, ℓ_1 option

Card 3 - first a, Δa, a option

Card 4 - first p, Δp, p option

Each of the above three cards, applying to ℓ_1, a and p, respectively, contain three items, separated by commas. The first item is the dimension of the first strip. If the third item (option) is o then the dimensions of the (N-1) strips following the first are successively incremented by the increment (Δ) of the second item. If the third item is 1 then the dimensions of the first $\frac{(N-1)}{2}$ strips following the first strip are successively incremented by the increment of the second item and the dimensions of the next $\frac{(N-1)}{2}$ strips are successively decremented by the same value. N must be odd when the option is 1. Note that one may use a negative number for the increment of item 2. Also note that the quantities ℓ_1, a and p are handled entirely independent of each other. If an increment value is o then there is no apodization in the corresponding quantity and the option is immaterial.

Card 5 - ΔH, Δr

These two quantities, separated by a comma, are here supplied.

Card 6 - heading

Only columns 1-20 are used for this card. For the normal modes case, the first ten columns on this card should contain NORM_MODE_. For independent conductors, the first ten columns should contain IND__COND_. This card serves as the top heading line on the plots as well as to signify the program whether the case is one of normal modes or uniform conductors.

Card 7 - heading

Card 8 - heading

Card 9 - heading

These three additional heading cards are required and will appear in order on the computer plots under the heading of card 6. Columns 1-70 may be used.

There follows a listing of the entire computer program as it is used on the CDC 6600 at Hanscom AFB, Ma. Omitted are the required control cards consisting of the standard job card, Fortran compile and execute cards and the standard control cards for plots.

```
      PROGRAM ROCT (INFUT,CLTPUT)
      DIMENSION PROGID(3)
      DIMENSION F(1200),FM(1200),FP(1200),CAP(1200),CAM(1200),VGM(1200),
     XPP(1200),PM(1200),RP(1200),RM(1200),RT(1200),PX(1200),SERP(1200),
     XSERM(1200),VNM(1200),VGP(1200)
      DIMENSION HEAD(2),HEAD1(7),HEAD2(7),HEAD3(7)
      DIMENSION FN(50),VM(50)
      COMMON FL,AL1,AL2,B,C,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
     X,LMODE
      READ *,H,T1,C,G,EL,FN,ETA
      READ *,ELBEGN,ELDEL,ELOPT
      READ *,ABEGIN,ADEL,AOPT
      READ *,PBEGIN,PDEL,POPT
      READ *,DELH,DIST
      READ 102,HEAD
      READ 100,HEAD1
      READ 101,HEAD2
      READ 101,HEAD3
      LMODE=1
      IF (HEAD(1) .EQ. "NORM MODE ") LMODE=2
      N=FN
      PL=30.
      PL=35.
      DO 41 I=1,N
      EL1(I)=ELBEGN+(I-1)*ELDEL
      AA(I)=ABEGIN+(I-1)*ADEL
41    PE(I)=PBEGIN+(I-1)*PDEL
      NEL=(N+1)/2
      IF (ELOPT .EQ. 0.) GO TO 42
      DO 43 I=NEL,N
43    EL1(I)=EL1(NEL)-(I-NEL)*ELDEL
42    IF ( AOPT .EQ. 0.) GO TO 44
      DO 45 I=NEL,N
45    AA(I)=AA(NEL)-(I-NEL)*ADEL
44    IF (POPT .EQ. 0.) GO TO 46
      DO 47 I=NEL,N
47    PE(I)=PE(NEL)-(I-NEL)*PDEL
46    CONTINUE
      FLO=2.8*SQRT(H*(H+1750.))
      FHI=2.8*(H+975.)
      FDEL=1.
      FBEG=AINT(FLO)+1.
      NF=INT(FHI)-INT(FLO)-1
      DO 40 I=1,NF
40    F(I)=FBEG+(I-1)*FDEL
      IF (F(1) .LT. FLO) PRINT *,"FREQUENCIES TOO LOW"
      IF (F(NF) .GT. FHI) PRINT *,"FREQUENCIES TOO HIGH"
      PRINT 60
      FACT=1.
      IF (ETA .GT. -2.) GO TO 4
      ETA=-1.
      FACT=(2./EN)**2
      PRINT *,"   PI GRATING CASE"
4     CONTINUE
      PRINT 61,H,T1,D,G,EL    ,EN,ETA,NF
      PRINT *,"  DELTA H = ",DELH,"  DISTANCE =",DIST
      PRINT *, "  R  LOSS   IS   " , RL
```

```
      PRINT 81,(I,EL1(I),I=1,N)
      PRINT 82,(I,AA(I),I=1,N)
      PRINT 83,(I,PE(I),I=1,N)
      PRINT 60
      IF (ETA .EQ. -1.) ELL =.87*.4E-8*EN
       IF (ETA .EQ. 1.) ELL=.23*.4E-8/EN
      ELL=0.
      DATA PROGID/8HSETHARES,4H3724,10HJ.WEINBERG/
      CALL FLTIO3(PROGID,200.,12.,1.)
      P=0.
      A=0.
      AY=0.
      PI=3.141592654
      PG=50.
      AYT=.5*AY*((1.-ETA)+EN*(1.+ETA))
      U0=4.*PI*1.E-7
      K=1
      I=1
      J=1
      OMH=H/1750.
   50 EF=F(K)
      OM=EF/(2.8*1750.)
      U11=1.-OMH/(OM**2-OMH**2)
      U22=U11
      U12=OM/(OM**2-OMH**2)
      B=SQRT(U11/U22)
      L=1
   30 IF (L .EQ. 2) GO TO 2
    1 S=1.
      GO TO 3
    2 S=-1.
    3 CONTINUE
      AL1=U22*B+S*U12
      AL2=U22*B-S*U12
       IF (J .GT. 1) GO TO 53
      CAO=.5*SQRT(U22/U11)*ALOG(1.+4.*SQRT(U11*U22)/
     X(U12**2-(SQRT(U11*U22)+1.)**2))
      CAO=CAO/D
   53 CONTINUE
      IF (I .EQ. 1) GO TO 51
        IF (J .EQ. 1) GO TO 51
      IF(L .EQ. 1) CAO=CAP(I-1)
      IF(L .EQ. 2) CAO=CAM(J-1)
   51 M=1
    5 DEL=.02*CAO
      CAOP=CAO+DEL
      CAOM=CAO-DEL
      CAOD=CAO*D
      CAOD=ABS(CAOD)
      CAOG=ABS(CAO*G)
      IF(CAOD .GT. 650.) GO TO 35
      IF(CAOG .GT. 650.) GO TO 35
      FTCO=FT(CAO)
      FTCP=FT(CAOP)
      FTCM=FT(CAOM)
      CA1=CAO-2.*DEL*FTCO/(FTCP-FTCM)
      IF(ABS(CA1) .GT. 1.E7) GO TO 35
```

```
      CA1D=CA1*D
      CA1D=ABS(CA1D)
      CA1G=ABS(CA1*G)
      IF(CA1D .GT. 650.) GO TO 35
      IF(CA1G .GT. 650.) GO TO 35
      FTC1=FT(CA1)
      IF (ABS((CA1-CA0)/CA0) .LT.  .001) GO TO 10
      CA0=CA1
      M=M+1
      IF(M .GT.10) GO TO 35
      GO TO 5
10    IF (L .EQ. 2) GO TO 20
      CA=CA1
      IF (ABS(FTC1) .GT. 1.) GO TO 35
      IF (CA .LT. 0.) GO TO 35
      FP(I)=EF
      CAP(I)=CA
      I=I+1
      L=2
      GO TO 30
20    CA=CA1
      IF (ABS(FTC1) .GT. 1.) GO TO 35
      IF (CA .LT. 0.) GO TO 35
      FM(J)=EF
      CAM(J)=CA
      J=J+1
       IF (J .EQ. I) GO TO 15
      IF (J .GT. I) GO TO 31
      I=J-1
      K=K-1
31    J=J-1
15    K=K+1
      IF (K .LE. NF) GO TO 50
      PRINT 60
      I1=I-1
      J1=J-1
      GO TO 24
35    PRINT *,"ITERATION DOES NOT CONVERGE.F= ",EF," S= ",S
      IF (L .EQ. 2) GO TO 15
      L=2
      GO TO 2
24    CONTINUE
      PRINT 63,(FP(I),CAP(I),I=1,I1,10)
      PRINT 64,(FM(J),CAM(J),J=1,J1,10)
      PRINT 60
      DO 22 J=1,J1
      IF (J .EQ. 1) VGM(J)=5./PI*(CAM(2)-CAM(1))/FDEL
      IF (J .EQ. J1) VGM(J)=5./PI*(CAM(J1)-CAM(J1-1))/FDEL
      IF (J .NE. 1 .AND. J .NE. J1) VGM(J)=
     X 5./PI*(CAM(J+1)-CAM(J-1))/FDEL*.5
22    CONTINUE
      PRINT 65,(FM(J),VGM(J),J=1,J1,10)
       PRINT 60
      DO 21 I=1,I1
      IF (I .EQ. 1) VGP(I)=5./PI*(CAP(2)-CAP(1))/FDEL
      IF (I .EQ. I1) VGP(I)=5./PI*(CAP(I1)-CAP(I1-1))/FDEL
      IF (I .NE. 1 .AND. I .NE. I1) VGP(I)=
```

```
   X5./PI*(CAP(I+1)-CAP(I-1))/FDEL*.5
21  CONTINUE
    PRINT 87,(FP(I),VGP(I),I=1,I1,10)
    J0=J1/2
    CAM0=CAM(J0)
    DO 23 J=1,J1
    CAMN=CAM0-CAM(J)
    CAMN=DIST*CAMN/PI
    CAMN=AMOD(CAMN,2.)
    IF (CAMN .GT. 1.) CAMN=CAMN-2.
    IF (CAMN .LT. -1.) CAMN=CAMN+2.
    VNM(J)=180.*CAMN
23  CONTINUE
    PRINT 62
    PRINT 86,(FM(J),VNM(J),J=1,J1,10)
    S=1.
    DO 25 I=1,I1
    FF=FP(I)
    CA=CAP(I)
    O=2.*PI*EF*1.E6
    OM=EF/(2.8*1750.)
    U11=1.-OMH/(OM**2-OMH**2)
    U22=U11
    U12=OM/(OM**2-OMH**2)
    B=SQRT(U11/U22)
    AL1=U22*B+S*U12
    AL2=U22*B-S*U12
    P1=(T(CA)+1.)**2*(TANH(CA*EL)-CA*EL*(SECH(CA*EL))**2)
    P2=(R1(CA)*EXP(CA*G)-R2(CA)*EXP(-CA*G))**2/4.
   X*(COTH(CA*T1)-CA*T1*(CSCH(CA*T1))**2)
    P3=.25*(R1(CA)**2)*(EXP(2.*CA*G)-1.)-.25*(R2(CA)**2)
   X*(EXP(-2.*CA*G)-1.)-R1(CA)*R2(CA)*CA*G
    P4=AL1*(T(CA)**2)*(EXP(2.*B*CA*D)-1.)-AL2*(EXP(-2.*B*CA*D)-1.)
   X-4.*B**2*U22*CA*D*T(CA)
    GECA=GE(CA)
    PP(I)=    O*U0   GECA    **2*(P1+P2+P3+P4)/8./CA**2*.5
    PP(I)=4.*PP(I)
    RP(I)=ABS(FP(I))/((1.-ETA)+(1.+ETA)*EN**2)*4.
    RP(I)=FACT*RP(I)
25  CONTINUE
    S=-1.
    DO 26 J=1,J1
    FF=FM(J)
    O=2.*PI*EF*1.E6
    CA=CAM(J)
    OM=EF/(2.8*1750.)
    U11=1.-OMH/(OM**2-OMH**2)
    U22=U11
    U12=OM/(OM**2-OMH**2)
    B=SQRT(U11/U22)
    AL1=U22*B+S*U12
    AL2=U22*B-S*U12
    P1=(T(CA)+1.)**2*(TANH(CA*EL)-CA*EL*(SECH(CA*EL))**2)
    P2=(R1(CA)*EXP(CA*G)-R2(CA)*EXP(-CA*G))**2/4.
   X*(COTH(CA*T1)-CA*T1*(CSCH(CA*T1))**2)
    P3=.25*(R1(CA)**2)*(EXP(2.*CA*G)-1.)-.25*(R2(CA)* 2)
   X*(EXP(-2.*CA*G)-1.)-R1(CA)*R2(CA)*CA*G
```

```
      P4=AL1*(T(CA)**2)*(EXP(2.*B*CA*D)-1.)-AL2*(EXP(-2.*E*CA*D)-1.)
     X-4.*B**2*U22*CA*D*T(CA)
      GECA=GE(CA)
      PM(J)=    D*UO* GECA    **2*(P1+P2+P3+P4)/ ./CA**2  .5
      PM(J)=4.*PM(J)
      RM(J)=ABS(PM(J))/((1.-ETA)+(1.+ETA)*EN**2)*4.
      RM(J)=FACT*RM(J)
   26 CONTINUE
      PRINT 60
      PRINT 71,(FP(I),RP(I),I=1,I1,10)
C     PRINT 72,(FM(J),RM(J),J=1,J1,5)
      IF (I1 .NE. J1) GO TO 90
       DO 84 I=1,I1
   84 RT(I)=RP(I)+RM(I)
      PRINT 60
      PRINT 75,(FP(I),RT(I),I=1,I1,10)
      FP1=FP(1)
      FPL=FP(I1)
      CALL FTRAN(RT,PX,I1,FP1,FPL)
      PRINT 60
      M=NM
       M=I1-1
      PRINT 73,(FP(I),PX(I),I=1,M ,20)
      DO 54 I=1,M
       XL=2.*PI*FP(I)*ELL
      XL=XL*1.E6
      L=I
      IF (I .EQ. 1) L=2
      SERP(I)= 20.*ALOG10((4.*RP(I)/RG)/
     X  ((1.+(RT(I)+RL)/RG)**2
     X                       +((PX(I)+XL)/RG)**2))
      SERP(I)=SERP(I)-76.4*DELH*DIST/
     X(2.*PI*1.E6*(FP(I+1)-FP(L-1))/(CAP(I+1)-CAP(L-1)))
      SERM(I)= 20.*ALOG10((4.*RM(I)/RG)/
     X  ((1.+(RT(I)+RL)/RG)**2
     X                       +((PX(I)+XL)/RG)**2))
      SERM(I)=SERM(I)-76.4*DELH*DIST/
     X(2.*PI*1.E6*(FM(I+1)-FM(L-1))/(CAM(I+1)-CAM(L-1)))
   54 CONTINUE
      PRINT 60
      PRINT 77,(FP(I),SERP(I),I=1,M ,10)
      PRINT 60
      PRINT 78,(FP(I),SERM(I),I=1,M ,10)
      XMIN=3500.
      DX=50.
      XMIN=2500.
      XMIN=2400.
      FREQO=.01*FREQ
      XMIN=AINT(FREQO)*100.
      XX=AINT(.01*FHI)-AINT(.01*FLO)+1.
      DX=100.
      YMIN=0.
      DY=200.
       DY=10000.
      DO 56 J=1,J1
      IF (CAM(J) .GT. 100000.) CAM(J)=100000.
      IF (VGM(J) .GT. 1000.) VGM(J)=1000.
```

```
96    CONTINUE
      DO 97 I=1,I1
      IF(CAP(I) .GT. 100000.) CAP(I)=100000.
      IF (VGP(I) .GT. 1000.) VGP(I)=1000.
97    CONTINUE
      CALL PLOT(1.5,0.,-3)
      CALL SYMBOL(.5,9.8,.1,HEAD,0,20)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL SYMBOL(.5,9.2,.1,HEAD3,0,70)
      CALL AXIS(0.,0.,21HWAVE NUMBER (+) (1/M),21,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FM,CAM,J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DY=100.
      CALL PLOT(16.,0.,-3)
      CALL AXIS(0.,0.,
     X                 25HGROUP DELAY/CM (+) (NSEC),25,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FM,VGM,J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DY=10000.
      CALL PLOT(16.,0.,-3)
      CALL AXIS(0.,0.,21HWAVE NUMBER (-) (1/M),21,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,CAP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DY=100.
      CALL PLOT(16.,0.,-3)
      CALL AXIS(0.,0.,
     X                 25HGROUP DELAY/CM (-) (NSEC),25,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,VGP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      YMIN=-180.
      DY=36.
      CALL PLOT(16.,0.,-3)
      CALL AXIS(0.,0.,22HNORMAL DISPERSION (+) ,22,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      JJ=0
58    CONTINUE
      DO 59 J=1,J1
      IF ((JJ+J) .GT. J1) GO TO 57
      FN(J)=FM(JJ+J)
      VM(J)=VNM(JJ+J)
      IF (J .EQ. 1) GO TO 59
      IF (VM(J) .LE. VM(J-1)) GO TO 59
      GO TO 57
59    CONTINUE
57    J2=J-1
      CALL LINE (FN,VM,J2,1,0,1,XMIN,DX,YMIN,DY,.08)
      JJ=JJ+J2
      IF ( (JJ+1) .LE. J1) GO TO 58
      YMIN=0.
      DY=30.
      DO 27 I=1,I1
      IF (RP(I) .GT. 300.) RP(I)=300.
      IF(RP(I) .GT. 2000.) RP(I)=2000.
27    CONTINUE
      CALL PLOT(16.,0.,-3)
      CALL AXIS (0.,0.,27HRAD. RES.,MINUS WAVE (OHMS),27,10.,90.,
```

```
     X  YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,RP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DO 28 J=1,J1
      IF (RM(J) .GT. 300.) RM(J)=300.
      IF (RM(J) .GT. 2000.) RM(J)=2000.
      IF (RT(J) .GT. 300.) RT(J)=300.
      IF (RT(J) .GT. 2000.) RT(J)=2000.
28    CONTINUE
      CALL PLOT(17.,0.,-3)
      CALL AXIS (0.,0.,27HRAD. RES., PLUS WAVE (OHMS),27,10.,90.,
     X  YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FM,RM,J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT(17.,0.,-3)
      CALL AXIS(0.,0.,22HRAD. RES. TOTAL (OHMS),22,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,RT,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      I1=M
      J1=M
      YMIN=-10000.
      YMIN=-250.
      DY=2000.
      DY=50.
      DO 92 I=1,I1
      IF (PX(I) .LT. -10000.) PX(I)=-10000.
      IF (PX(I) .LT. -250.) PX(I)=-250.
      IF (PX(I) .GT. 10000.) PX(I)=10000.
      IF (PX(I) .GT.  250.) PX(I)=250.
92    CONTINUE
      CALL PLOT(17.,0.,-3)
      CALL AXIS(0.,0.,22HRAD. REAC TOTAL (OHMS),22,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,PX,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DO 93 I=1,I1
       IF (SERP(I) .LT. -80. ) SERP(I)=-80.
       IF (SERM(I) .LT. -80. ) SERM(I)=-80.
93    CONTINUE
      YMIN=-80.
        DY=10.
      CALL PLOT(16.,0.,-3)
      CALL SYMBOL(.5,9.8,.1,HEAD,0,20)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL SYMBOL(.5,9.2,.1,HEAD3,0,70)
      CALL AXIS(0.,0.,26H-INS. LOSS,MINUS WAVE (DB),26, 8.,90.,YMIN,
     X  DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,SERP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT(16.,0.,-3)
      CALL SYMBOL(.5,9.8,.1,HEAD,0,20)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL SYMBOL(.5,9.2,.1,HEAD3,0,70)
      CALL AXIS(0.,0.,26H-INS. LOSS, PLUS WAVE (DB),26, 8.,90.,YMIN,
     X  DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
```

```
      CALL LINE(FM,SFRM,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL ENDPLT
      STOP
 90   PRINT 76
      STOP
 60   FORMAT(1H1)
 61   FORMAT(5X," H= ",E15.7/5X," T1= ",E15.7/5X," D= ",E15.7/
     X5X," G= ",E15.7/5X," L= ",E15.7/
     X5X," N= ",E15.7/5X,"ETA=",E15.7////9X,"NO. OF F'S ARE ",I5)
 62   FORMAT(//10(5F15.5/))
 63   FORMAT(///50X,"S=1"//(10X,"F= ",E15.7,10X,"K (-) =  ",E15.7/))
 64   FORMAT(///50X,"S=-1"//(10X,"F= ",E15.7,10X,"K (+)  = ",E15.7/))
 66   FORMAT(///(10X,"F= ",E15.7,10X,"P (-)  = ",E15.7/))
 67   FORMAT(///(10X,"F= ",E15.7,10X,"P (+)  = ",E15.7/))
 66   FORMAT(///5X,"L1= ",E15.7/5X,"A= ",E15.7/5X,"P= ",E15.7/
     X5X,"IC= ",E15.7/5X,"N= ",E15.7/5X,"ETA= ",E15.7)
 71   FORMAT(///(10X,"F= ",E15.7,10X,"RAD. RES. (-)   = ",E15.7/))
 72   FORMAT(///(10X,"F= ",E15.7,10X,"RAD. RES. (+)    = ",E15.7/))
 73   FORMAT( //(10X,"F= ",E15.7,10X,"RAD. REAC. TOTAL= ",E15.7/))
 75   FORMAT(///(10X,"F= ",E15.7,10X,"RAD. RES. TOTAL = ",E15.7/))
 76   FORMAT ("1  A K ROOT EXISTS FOR ONE WAVE ONLY")
 77   FORMAT(//(10X,"F= ",E15.7,10X,"INS. LOSS  (-)  = ",E15.7/))
 78   FORMAT(//(10X,"F= ",E15.7,10X,"INS. LOSS (+)  = ",E15.7/))
 81   FORMAT(//(10X,"L1(",I4,")= ",E15.7/))
 82   FORMAT(//(10X," A(",I4,")= ",E15.7/))
 83   FORMAT(//(10X," P(",I4,")= ",E15.7/))
 85   FORMAT(/(10X," F= ",E15.7,10X,"GROUP DELAY (+) = ",E15.7/))
 86   FORMAT("    F= ",E15.7,"  NORM DISPERSION (+) = ",E15.7)
 87   FORMAT("    F=  ",E15.7,"    GROUP DELAY (-) =  ",E15.7)
102   FORMAT(2A10)
100   FORMAT(7A10)
101   FORMAT(7A10)
      END
```

```
      FUNCTION SECH(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      SECH=0.
      IF (CA .LE. 740.) SECH=1./COSH(CA)
      RETURN
      END

      FUNCTION CSCH(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      CSCH=0.
      IF (CA .LE. 740.) CSCH=1./SINH(CA)
      RETURN
      END

      FUNCTION COTH(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      COTH  =1./TANH(CA)
      RETURN
      END

      FUNCTION T(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      T     =(AL2+TANH(CA*EL))/(AL1-TANH(CA*EL))
      RETURN
      END

      FUNCTION R1(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
       R1   =(1.-AL2)*EXP(-B*CA*D)+(1.+AL1)*T(CA)*EXP(B*CA*D)
      RETURN
      END

      FUNCTION R2(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      R2    =(1.+AL2)*EXP(-B*CA*D)+(1.-AL1)*T(CA)*EXP(B CA*D)
      RETURN
      END

      FUNCTION FT(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      FT    =.5*((COTH(CA*T1)-1.)*R2(CA)*EXP(-CA*G)*EXP(-B*CA*D)
     X-(COTH(CA*T1)+1.)*R1(CA)*EXP(CA*G)*EXP(-B*CA*D))
      RETURN
      END
```

```
      FUNCTION FT1(CA)
      COMMON FL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      FTT     =EXP(-B*CA*D)*(R1(CA)*EXP(CA*G)-R2(CA)*EXP(-CA*G))
     X*S*T1*(CSCH(CA*T1))**2
      FTT2=
     X-S*G*EXP(-B*CA*D)*((COTH(CA*T1)+1.)*R1(CA)*EXP(CA G)
     X+(COTH(CA*T1)-1.)*R2(CA)*EXP(-CA*G))
      FTT3=
     X+2.*B*S*D*EXP(-2.*B*CA*D)*((COTH(CA*T1)+1.)*(1.-AL2)
     X*EXP(CA*G)-(COTH(CA*T1)-1.)*(1.+AL2)*EXP(-CA*G))
      FTT5=
     X+S*EL*(AL1+AL2)*(SECH(CA*EL)**2)/(AL1-TANH(CA*EL))**2
      FTT6=
     X ((COTH(CA*T1)-1.)*(1.-AL1)*EXP(-CA*G)-(COTH(CA*T1)+1.)
     X*(1.+AL1)*EXP(CA*G))
      FTT4=FTT5*FTT6
      FT1=.5*(FTT+FTT2+FTT3+FTT4)
      RETURN
      END

      FUNCTION SINC(CA)
      COMMON FL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
      PI=3.141592654
      SINC=(SIN(PI*CA))/(PI*CA)
      RETURN
      END


      FUNCTION GAY(CA)
      COMPLEX C,CS
      COMMON FL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
     X,LMODE
      PI=3.141592654
      N=EN
      C=CMPLX(0.,0.)
      DO 1 I=1,N
      CS=CMPLX(COS(CA*I*PE(I)),-SIN(CA*I*PE(I)))
      IF (LMODE .EQ. 2) GO TO 2
      C=C+SINC(.5*AA(I)*CA/PI)*ETA**I*SQRT(EL1(I))*CS
      GO TO 3
    2 CONTINUE
      C=C+SINC(2.*AA(I)/(PE(I)*(3.-ETA)))*
     XSINC((CA*PE(I)*.5/PI)    -.25 *(3.+ETA))*ETA**I*SQRT(EL1(I))*CS
    3 CONTINUE
    1 CONTINUE
      GAY=CABS(C)
      RETURN
      END

      FUNCTION GE(CA)
      COMMON FL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
      GE     =ABS(GAY(CA) *EXP(-B*CA*D)/FT1(CA))
      RETURN
      END
```

```
      SUBROUTINE HTRAN(R,X,N,FBEG,FEND)
      DIMENSION R(3),X(3)
      PI=3.14159265359
      FDEL=(FEND-FBEG)/(N-1)
      F=FBEG+.5*FDEL
      INC=MOD(N,2)
      NI=N+INC-1
       NM1=N-1
      NIM2=NI-2
      DO 33 I=1,NM1
      X(I)=0.
      IF (I .EQ. 1) RX=(3.*R(1)+6.*R(2)-R(3))/8.
      IF (I .EQ. NM1) RX=(-R(N-2)+6.*R(NM1)+3.*R (N))/8.
      IF (I .EQ. 1 .OR. I .EQ. NM1) GO TO 20
      RX=(-R(I-1)+9.*R(I)+9.*R(I+1)-R(I+2))/16.
   20 CONTINUE
      FI=FBEG
      DO 28 IP=1,NIM2,2
      X(I)=X(I)+4.*(R(IP+1)-RX)/(( FI+FDEL)**2-F**2)
     X          +2.*(R(IP   )-RX)/(   FI        **2-F**2)
      FI=FI+2.*FDEL
   28 CONTINUE
      FEN=FEND
      IF(INC .EQ. 0 ) FEN=FEND-FDEL
      X(I)=X(I)+(R(NI)-RX)/(FEN**2-F**2)
     X          -(R(1  )-RX)/(FBEG**2-F**2)
      X(I)=FDEL/3.*X(I)
      IF(INC .EQ.1) GO TO 30
      X(I)=X(I)+.5*FDEL*((R(NI)-RX)/(FEN**2-F**2)
     X          +(R(N)-RX)/(FEND**2-F**2))
   30 X(I)=2./PI*F*X(I)+RX/PI*ALOG
     X ((1.-F/FEND)/(1.+F/FEND)*(F+FBEG)/(F-FBEG))
      F=F+FDEL
   33 CONTINUE
      NM2=N-2
      X1=(15.*X(1)-10.*X(2)+3.*X(3))/8.
       X2=(3.*X(1)+6.*X(2)-X(3))/8.
      DO  31 I=3,NM2
      XT=(-X(I-2)+9.*X(I-1)+9.*X(I)-X(I+1))/16.
      X(I-2)=X1
      X1=X2
      X2=XT
   31 CONTINUE
      X(N)=(15.*X(NM1)-10.*X(NM2)+3.*X(N-3))/8.
      X(N-1)=(3.*X(NM1)+6.*X(NM2)-X(N-3))/8.
      X(N-2)=X2
      X(N-3)=X1
      RETURN
      END
```

B. Microstrip Model

A second computer program incorporating the microstrip model has also been completed for the CDC 6600 at Hanscom AFB, Ma. The physical quantities graphically displayed by this program are the wave number, group delay and insertion loss for both solutions, normalized dispersion for the + wave, input resistance, corresponding reactance and the magnitude of the impedance. Print out is provided by the program as for the basic theory model.

Note that apodization and normal modes are not permitted here and that additional input constants are required. Thus the use of the input cards are modified from the basic theory program by the following:

Cards 2-4 - The increment values are always o and the option values should be o.

Card 5A - Z_{c1}, $\overline{\beta}_c$, σ, α_{cK}

This is a new card to be inserted between card 5 and card 6. The indicated constants, required by the microstrip model, are to be inserted here, separated by commas.

Card 6 - columns 1-70 may be used. The first ten columns should contain IND__COND_.

The listing of the entire program, except for control cards which are the same as for the basic theory program, now follows.

```
      PROGRAM ROOT (INPUT,OUTPUT)
      DIMENSION PROBID(7)
      DIMENSION F(1200),FM(1200),FP(1200),CAP(1200),CAM(1200),VGM(1200),
     XRP(1200),PM(1200),PP(1200),RM(1200),RT(1200),PX(1200),SERP(1200),
     XSERM(1200),VNM(1200),VGP(1200),RN(1200),XN(1200),ZM(1200)
      DIMENSION HEAD(7),HEAD1(7),HEAD2(7),HEAD3(7)
      DIMENSION FN(50),VM(50)
      COMMON EL,AL1,AL2,R,D,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
     X,LMODE
      READ *,H,T1,D,G,EL,EN,ETA
      READ *,ELBEGN,ELDEL,ELOPT
      READ *,ABEGIN,ADEL,AOPT
      READ *,PBEGIN,PDEL,POPT
      READ *,DELH,DIST
      READ *,ZC,RTC,SIG,ACC
      READ 100,HEAD
      READ 100,HEAD1
      READ 100,HEAD2
      READ 100,HEAD3
      LMODE=1
      IF (HEAD(1) .EQ. "NORM MODE ") LMODE=2
      N=EN
      DO 41 I=1,N
      EL1(I)=ELBEGN+(I-1)*ELDEL
      AA(I)=ABEGIN+(I-1)*ADEL
   41 PE(I)=PBEGIN+(I-1)*PDEL
      NEL=(N+1)/2
      IF (ELOPT .EQ. 0.) GO TO 42
      DO 43 I=NEL,N
   43 EL1(I)=EL1(NEL)-(I-NEL)*ELDEL
   42 IF (AOPT .EQ. 0.) GO TO 44
      DO 45 I=NEL,N
   45 AA(I)=AA(NEL)-(I-NEL)*ADEL
   44 IF (POPT .EQ. 0.) GO TO 46
      DO 47 I=NEL,N
   47 PE(I)=PE(NEL)-(I-NEL)*PDEL
   46 CONTINUE
      FLO=2.*SQRT(H*(H+1750.))
      FHI=2.*(H+ 75.)
      FDEL=1.
      FBEG=AINT(FLO)+1.
      NF=INT(FHI)-INT(FLO)-1
      DO 49 I=1,NF
   49 F(I)=FBEG+(I-1)*FDEL
      IF (F(1) .LT. FLO) PRINT *,"FREQUENCIES TOO LOW"
      IF (F(NF) .GT. FHI) PRINT *,"FREQUENCIES TOO HIGH"
      PRINT 6[illegible]
      FACT=1.
      IF (ETA .GT. -2.) GO TO 4
      ETA=-1.
      FACT=(2./EN)**2
      PRINT *,"    BR GRATING CASE"
    4 CONTINUE
      PRINT 61,H,T1,D,G,EL,[illegible],EN,ETA,NF
      PRINT *,"  DELTA H = ",DELH,"  DISTANCE =",DIST
      PRINT *,"  SIGMA TO  ",SIG
      PRINT 62,(I,EL1(I),I=1,N)
```

```
      PRINT 82,(I,AA(I),I=1,N)
      PRINT 83,(I,RF(I),I=1,N)
      PRINT 60
      IF (ETA .EQ. -1.) ELL =.87*.4E-6*EN
       IF (ETA .EQ. 1.) ELL=.23*.4E-8/EN
      ELL=1.
      DATA PROGID/4HS, THARES,4H3724,10HJ.WEINBERG/
      CALL FLTID3(PROGID,200.,12.,1.)
      P=0.
      A=0.
      AY=0.
      PI=3.14159265
      FG=F0.
      AYT=.5*AY*((1.-ETA)+EN*(1.+ETA))
      U0=4.*PI*1.E-7
      EPR=10.
      EP0=1./(36.E9*PI)
      H0=T1
      R0=AA(1)
      EP=EP0*EPR
      FT=F0.
      K=1
      I=1
      J=1
      OMH=H/1750.
50    FF=F(K)
      OM=FF/(2.8E10*10.)
      U11=1.-OMH/(OM**2-OMH**2)
      U22=U11
      U12=OM/(OM**2-OMH**2)
      R=SQRT(U11/U22)
      L=1
30    IF (L .EQ. 2) GO TO 2
 1    S=1.
      GO TO 3
 2    S=-1.
 3    CONTINUE
      AL1=U22*R+S*U12
      AL2=U22*R-S*U12
       IF (J .GT. 1) GO TO 53
      CA0=.5*SQRT(U22/U11)*ALOG(1.+4.*SQRT(U11*U22)/
     Y(U12**2-(SQRT(U11*U22)+1.)**2))
      CA0=CA0/P
53    CONTINUE
      IF (I .EQ. 1) GO TO 51
        IF (J .EQ. 1) GO TO 51
      IF(L .EQ. 1) CA0=CAP(I-1)
      IF(L .EQ. 2) CA0=CAM(J-1)
51    M=1
 5    DEL=.02*CA0
      CA0P=CA0+DEL
      CA0M=CA0-DEL
      CA0R=CA0*R
      CA0D=ABS(CA0P)
      CA0C=ABS(CA0*C)
      IF(CA0D .GT. 650.) GO TO 35
      IF(CA0C .GT. 650.) GO TO 35
```

```
      FTCO=FT(CAO)
      FTCP=FT(CAOP)
      FTCM=FT(CAOM)
      CA1=CAO-2.*DEL*FTCO/(FTCP-FTCM)
      IF(ABS(CA1) .GT. 1.57) GO TO 35
      CA1F=CA1*D
      CA1D=ABS(CA1D)
      CA1G=ABS(CA1*C)
      IF(CA1D .GT. 650.) GO TO 35
      IF(CA1G .GT. 650.) GO TO 35
      FTC1=FT(CA1)
      IF (ABS((CA1-CAO)/CAO) .LT. .001) GO TO 10
      CAO=CA1
      M=M+1
      IF(M .GT.10) GO TO 35
      GO TO 5
10    IF (L .EQ. 2) GO TO 20
      CA=CA1
      IF (ABS(FTC1) .GT. 1.) GO TO 35
      IF (CA .LT. 0.) GO TO 35
      FP(I)=EF
      CAP(I)=CA
      I=I+1
      L=2
      GO TO 3
20    CA=CA1
      IF (ABS(FTC1) .GT. 1.) GO TO 35
      IF (CA .LT. 0.) GO TO 35
      FM(J)=EF
      CAM(J)=CA
      J=J+1
      IF (J .EQ. I) GO TO 15
      IF (J .GT. I) GO TO 31
      I=J-1
      K=K-1
31    J=J-1
15    K=K+1
      IF (K .LE. NE) GO TO 50
      PRINT 
      I1=I-1
      J1=J-1
      GO TO 2
35    PRINT *,"ITERATION DOES NOT CONVERGE.F= ",EF," S= ",S
      IF (L .EQ. 2) GO TO 15
      L=2
      GO TO 2
24    CONTINUE
      PRINT 87,(FP(I),CAP(I),I=1,I1,10)
      PRINT 84,(FM(J),CAM(J),J=1,J1,10)
      PRINT 
      DO  J=1,J1
      IF (J .EQ. 1) VGM(J)=5./PI*(CAM(2)-CAM(1))/FDEL
      IF (J .EQ. J1) VGM(J)=5./PI*(CAM(J1)-CAM(J1-1))/FDEL
      IF (J .NE. 1 .AND. J .NE. J1) VGM(J)=
     X   ./PI*(CAM(J+1)-CAM(J-1))/FDEL*.5
      CONTINUE
      PRINT  ,(FM(J),VGM(J),J=1,J1,10)
```

```
      [illegible]
      DO 21 I=1,I1
      IF (I .EQ. 1) VGP(I)=6./PI*(CAP(2)-CAP(1))/FREL
      IF (I .EQ. I1) VGP(I)=6./PI*(CAP(I1)-CAP(I1-1))/FREL
      IF (I .NE. 1 .AND. I .NE. I1) VGP(I)=
     X6./PI*(CAP(I+1)-CAP(I-1))/FREL*.5
   21 CONTINUE
      PRINT 52,(FP(I),VGP(I),I=1,I1,10)
      J1=J1/2
      [illegible]CAM(J1)
      [illegible] 1,J1
      CAMN=CAM1-CAM(J)
      CAMN=[illegible]CAMN/PI
      CAMN=AMOD(CAMN,2.)
      IF (CAMN .GT. 1.) CAMN=CAMN-2.
      IF (CAMN .LT. -1.) CAMN=CAMN+2.
      [illegible](J)=1[illegible]MN
   23 CONTINUE
      PRINT 5[illegible]
      PRINT [illegible],(FM(J),VNM(J),J=1,J1,10)
      [illegible]1.
      [illegible] I=1,I1
      [illegible]FP(I)
      [illegible]AF(I)
      [illegible]
      OM[illegible]F/(2.[illegible]*1[illegible]0.)
      [illegible]1.-OMH/(OM**2-OMH**2)
      [illegible]
      [illegible]OM/(OM**2-OMH**2)
      [illegible]SQRT([illegible]1/[illegible])
      [illegible]
      [illegible]
      P1=[illegible]+1.)[illegible]*(TANH(CA*EL)-CA*EL*(SECH(CA*EL))**2)
      [illegible]EXP(CA*G)-F2(CA)*EXP(-CA*G))**2/4.
     X*([illegible]T1)-C[illegible]*T1*(COCH(CA*T1))**2)
      P3[illegible](F1(CA)**2)*(EXP(2.*CA*G)-1.)-.25*(F2(CA)**2)
     X*(EXP(-2.*[illegible])-1.)-F1(CA)*F2(CA)*CA*G
      P4=[illegible](T(CA)**2)*(EXP(2.*B*CA*D)-1.)-AL2*(EXP(-2.*B*CA*D)-1.)
     X[illegible]CA-[illegible]*T(CA)
      [illegible](CA)
      [illegible](I)=[illegible]**2*(P1+P2+P3+P4)/[illegible]./CA**2*.5
      [illegible](I)=4.*[illegible](I)
      [illegible](I)=A[illegible](RP(I))/((1.-ETA)+(1.+ETA)[illegible])*4.
      [illegible]
      FACT1=(SIN([illegible]CAP(I)*PE(1)/2.)/SIN(CAP(I)*PE(1)/2.))**2
      FACT2=(SIN([illegible]*CAP(I)*PE(1)/2.)/COS(CAP(I)*PE(1)/2.))**2
      IF (ETA .EQ. 1.) RP(I)=RP(I)*FACT1
      IF (ETA .EQ. -1.) RP(I)=RP(I)*FACT2
C     [illegible] IS FIRST COMPUTED AS FOR N=1. IT IS THEN
C     MULTIPLIED BY 1 FACTOR FOR ETA =1 AND BY ANOTHER FACTOR FOR ETA=-1 AND N
C     [illegible]IZATION IS NOT PERMITTED.
   2[illegible] CONTINUE
      [illegible]
      [illegible] J=1,J1
      [illegible]M(J)
      [illegible]
      [illegible]AM(J)
```

```
      OMH=F/(2.*PI*RO.)
      U11=1.-OMH/(OM**2-OMH**2)
      U  =U11
      U12=OM/(OM**2-OMH**2)
      [illegible](U11/U12)
      AL1=U22*D+S*U12
      AL2=U22*D-S*U12
      P1=(T(CA)+1.)**2*(TANH(CA*EL)-CA*EL*(SECH(CA*EL))**2)
      P2=(F1(CA)*EXP(CA*G)-F2(CA)*EXP(-CA*G))**2/4.
     X*(COTH(CA*T1)-CA*T1*(CSCH(CA*T1))**2)
      P3=.5*(R1(CA)**2)*(EXP(2.*CA*G)-1.)-.25*(R2(CA)**2)
     X*(EXP(-2.*CA*G)-1.)-R1(CA)*R2(CA)*CA*G
      P4=AL1*(T(CA)**2)*(EXP(2.*B*CA*D)-1.)-AL2*(EXP(-2.*B*CA*D)-1.)
     X-4.*U12*B*(U22*CA*D)*T(CA)
      G=F2(CA)
      OM(J)=[illegible]**2*(P1+P2+P3+P4)/8./CA**2 .5
      OM(J)=2.*OM(J)
      M(J)=ABS(FM(J))/((1.-ETA)+(1.+ETA)     )*4.
      RM(J)=FACT*FM(J)
      FACT1=(SIN(N*CAM(J)*PF(1)/2.)/SIN(CAM(J)*PF(1)/2.))**2
      FACT2=(SIN(N*CAM(J)*PF(1)/2.)/COS(CAM(J)*PF(1)/2.))**2
      IF(ETA.EQ.1.) RM(J)=RM(J)*FACT1
      IF(ETA.EQ.-1.) RM(J)=RM(J)*FACT2
C     [illegible] IS FIRST COMPUTED AS FOR N=1. IT IS THEN
C     MULTIPLIED BY 1 FACTOR FOR ETA=1 AND BY ANOTHER FACTOR FOR ETA=-1 AND N
C     [illegible] APPROXIMATION IS NOT PERMITTED.
 25   CONTINUE
      PRINT 60
      PRINT 71,(FP(I),RP(I),I=1,I1,10)
      PRINT 72,(FM(J),RM(J),J=1,J1,5)
      IF (I1 .NE. J1) GO TO 90
      DO   I=1,I1
      [illegible](I)=RP(I)+RM(I)
      PRINT [illegible]
      PRINT 73,(FP(I),RT(I),I=1,I1,10)
      FP1=FP(1)
      FPL=FP(I1)
      CALL [illegible](T,DX,I1,FP1,FPL)
      [illegible]
      M=I1-1
      PRINT 7[illegible],(FP(I),DX(I),I=1,M,20)
      [illegible]
      DO   I=1,M
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible](I)/SI(I)/(2*ZC)
      IF ([illegible] .EQ. -1.) GO TO 231
      [illegible]
      [illegible]
      [illegible]
      [illegible]
      [illegible]
```

```
      AR=AR/FN
202   CONTINUE
      ARC=AR+AC
      DIN=1.+COS(2.*PI*FL1(1))*SECH(2.*ARC*FL1(1))
      RIN=ZO*TANH(2.*ARC*FL1(1))/DIN
      IF (ABS(RIN) .LE. .0001) RIN=ABS(RIN)
      XIN=ZO*SIN(2.*PI*FL1(1))*SECH(2.*ARC*FL1(1))/DIN
      RN(I)=RIN
      XN(I)=XIN
      ZN(I)=SQRT(RIN**2+XIN**2)
      RC=RIN*AC/(AC+RTT   /ZO)
      XL=XIN*RT/(RT+RXX   /ZO)
      RIMP=RIN*RPP   /ZO/(AC+RTT   /ZO)
      RIMM=RIN*RMM   /ZO/(AC+RTT   /ZO)
      RIM=RIMP+RIMM
      XIM=XIN*RXX   /ZO/(RT+RXX   /ZO)
      DSER=(RT+RIN)**2+XIN**2
      L=I
      IF (I .EQ. 1) L=2
      SERP(I)=20.*ALOG10((4.*RI*RIMP              )/DSER)
      SERP(I)=SERP(I)-76.4*DELH*DIST/
     X(2.*PI*1.E6*(FP(I+1)-FP(L-1))/(CAP(I+1)-CAP(L-1)))
      SERM(I)=20.*ALOG10((4.*RI*RIMM              )/DSER)
      SERM(I)=SERM(I)-76.4*DELH*DIST/
     X(2.*PI*1.E6*(FM(I+1)-FM(L-1))/(CAM(I+1)-CAM(L-1)))
84    CONTINUE
      PRINT 6
      PRINT 77,(FP(I),SERP(I),I=1,M ,10)
      PRINT 8
      PRINT 77,(FM(I),SERM(I),I=1,M ,10)
      FREQO=.01*FREQ
      XMIN=AINT(FREQO)*100.
      XY=AINT(.01*FHI)-AINT(.01*FLO)+1.
      DX=100.
      YMIN=0.
      DY=10000.
      DO 96 J=1,J1
      IF (CAM(J) .GT. 100000.) CAM(J)=100000.
      IF (VGM(J) .GT. 1000.) VGM(J)=1000.
96    CONTINUE
      DO 97 I=1,I1
      IF(CAP(I) .GT. 100000.) CAP(I)=100000.
      IF (VGP(I) .GT. 1000.) VGP(I)=1000.
97    CONTINUE
      CALL PLOT(1.5,0.,-3)
      CALL SYMBOL(.5,9.8,.1,HEAD,0.,70)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0.,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0.,70)
      CALL SYMBOL(.5,9.2,.1,HEAD3,0.,70)
      CALL AXIS(0.,0.,21HWAVE NUMBER (+) (1/M),21,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FM,CAM,J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DY=100.
      CALL PLOT(15.,0.,-3)
      CALL AXIS(0.,0.,
     X                25HGROUP DELAY/CM (+) (NSEC),25,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
```

```
      CALL LINE(FM,VGM,J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DY=1000.
      CALL PLOT(15.,0.,-3)
      CALL AXIS(0.,0.,21HWAVE NUMBER (-) (1/M),21,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,CAP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DY=100.
      CALL PLOT(15.,0.,-3)
      CALL AXIS(0.,0.,
     X          25HGROUP DELAY/CM (-) (NSEC),25,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,VGP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      YMIN=-100.
      DY=50.
      CALL PLOT(15.,0.,-3)
      CALL AXIS(0.,0.,22HNORMAL DISPERSION (+) ,22,10., 0.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      JJ=0
   56 CONTINUE
      DO 58 J=1,J1
      IF ((JJ+J) .GT. J1) GO TO 57
      FN(J)=FM(JJ+J)
      VM(J)=VGM(JJ+J)
      IF (J .EQ. 1) GO TO 58
      IF (VM(J) .LE. VM(J-1)) GO TO 59
      GO TO 58
   58 CONTINUE
   57 J2=J-1
      CALL LINE (FN,VM,J2,1,0,1,XMIN,DX,YMIN,DY,.08)
      JJ=JJ+J2
      IF ( (JJ+1) .LT. J1) GO TO 56
      I1=M
      J1=M
      YMIN=0.
      DY=50.
      DO 72 I=1,I1
      IF (RN(I) .LT. 0.) RN(I)=0.
      IF (RN(I) .GT. 300.) RN(I)=300.
      IF (ZM(I) .GT. 300.) ZM(I)=300.
   72 CONTINUE
      CALL PLOT(15.,0.,-3)
      CALL AXIS (0.,0.,27H   INPUT RESISTANCE  (OHMS),27,10.,90.,
     X  YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,RN,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT(15.,0.,-3)
      CALL AXIS (0.,0.,27H IMPEDANCE MAGNITUDE (OHMS),27,10.,90.,
     X  YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,ZM,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      YMIN=-250.
      DY=50.
      DO 92 I=1,I1
      IF (XN(I) .LT. -250.) XN(I)=-250.
      IF (XN(I) .GT. 250.) XN(I)=250.
   92 CONTINUE
      CALL PLOT(15.,0.,-3)
```

```
      CALL AXIS(0.,0.,22HINPUT REACTANCE (OHMS),22,10.,90.,YMIN,DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,YN,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DO 93 I=1,I1
       IF (SERP(I) .LT. -80. ) SERP(I)=-80.
       IF (SERM(I) .LT. -80. ) SERM(I)=-80.
   93 CONTINUE
      YMIN=-80.
        DY=10.
      CALL PLOT(18.,0.,-3)
      CALL SYMBOL(.5,9.8,.1,HEAD,0,70)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL SYMBOL(.5,9.2,.1,HEAD3,0,70)
      CALL AXIS(0.,0.,26H-INS. LOSS,MINUS WAVE (DB),26, 8.,90.,YMIN,
     Y DY,10.)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FP,SERP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT(18.,0.,-3)
      CALL SYMBOL(.5,9.8,.1,HEAD,0,70)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL SYMBOL(.5,9.2,.1,HEAD3,0,70)
      CALL AXIS(0.,0.,26H-INS. LOSS, PLUS WAVE (DB),26, 8.,90.,YMIN,
     Y DY,10.)
      CALL AXIS ( 0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,10.)
      CALL LINE(FM,SERM,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL ENDPLT
      STOP
   99 PRINT 76
      STOP
   60 FORMAT(1H1)
   61 FORMAT(5X," H= ",E15.7/5X," T1= ",E15.7/5X," D= ",E15.7/
     X5X," C= ",E15.7/5X," L= ",E15.7/
     Y5X," N= ",E15.7/5X,"ETA=",E15.7////5X,"NO. OF F'S ARE ",I5)
   62 FORMAT(//10(E15.3/))
   63 FORMAT(///5X,"S=1"//(10X,"F= ",E15.7,10X,"K (-) = ",E15.7/))
   64 FORMAT(///5X,"S=-1"//(10X,"F= ",E15.7,10X,"K (+)  = ",E15.7/))
   66 FORMAT(///(10X,"F= ",E15.7,10X,"P (-)  = ",E15.7/))
   67 FORMAT(///(10X,"F= ",E15.7,10X,"P (+)  = ",E15.7/))
   68 FORMAT(///5X,"L1= ",E15.7/5X,"A= ",E15.7/5X,"P= ",E15.7/
     X5X,"T = ",E15.7/5X,"N= ",E15.7/5X,"ETA= ",E15.7)
   71 FORMAT(///(10X,"F= ",E15.7,10X,"RAD. RES. (-)  = ",E15.7/))
   72 FORMAT(///(10X,"F= ",E15.7,10X,"RAD. RES. (+)   = ",E15.7/))
   73 FORMAT( ///(10X,"F= ",E15.7,10X,"RAD. REAC. TOTAL= ",E15.7/))
   75 FORMAT(///(10X,"F= ",E15.7,10X,"RAD. RES. TOTAL = ",E15.7/))
   76 FORMAT ("1  A K ROOT EXISTS FOR ONE WAVE ONLY")
   77 FORMAT(//(10X,"F= ",E15.7,10X,"INS. LOSS  (-) = ",E15.7/))
   78 FORMAT(///(10X,"F= ",E15.7,10X,"INS. LOSS (+)  = ",E15.7/))
   81 FORMAT(//(10X,"L1(",I4,")= ",E15.7/))
   82 FORMAT(//(10X," A(",I4,")= ",E15.7/))
   83 FORMAT(//(10X," P(",I4,")= ",E15.7/))
   85 FORMAT(//(10X," F= ",E15.7,10X,"GROUP DELAY (+) = ",E15.7/))
   86 FORMAT("   F= ",E15.7,"  NORM DISPERSION (+) = ",E15.7)
   87 FORMAT("   F= ",E15.7,"    GROUP DELAY (-) =  ",E15.7)
  100 FORMAT(7A10)
      END
```

```
      FUNCTION SECH(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      SECH=0.
      IF (CA .LE. 740.) SECH=1./COSH(CA)
      RETURN
      END


      FUNCTION CSCH(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      CSCH=0.
      IF (CA .LE. 740.) CSCH=1./SINH(CA)
      RETURN
      END


      FUNCTION COTH(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      COTH   =1./TANH(CA)
      RETURN
      END


      FUNCTION T(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      T      =(AL2+TANH(CA*EL))/(AL1-TANH(CA*EL))
      RETURN
      END


      FUNCTION P1(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
       P1     =(1.-AL2)*EXP(-B*CA*D)+(1.+AL1)*T(CA)*EXP(B*CA*D)
      RETURN
      END

      FUNCTION P2(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      P2     =(1.+AL2)*EXP(-B*CA*D)+(1.-AL1)*T(CA)*EXP(B CA*D)
      RETURN
      END


      FUNCTION FT(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      FT     =.5*((COTH(CA*T1)-1.)*P2(CA)*EXP(-CA*G)*EXP(-B*CA*D)
     X-(COTH(CA*T1)+1.)*P1(CA)*EXP(CA*G)*EXP(-B*CA*D))
      RETURN
      END
```

```
      FUNCTION GAY(CA)
      COMPLEX C,CS
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
     X,LMODE
      PI=3.14159265
      N=EN
C   FOR N>1,RAD. RES. IS FIRST COMPUTED AS FOR N=1. IT IS THEN
C   MULTIPLIED BY 1 FACTOR FOR ETA =1 AND BY ANOTHER FACTOR FOR ETA=-1 AND N
C    EVEN.  APODIZATION IS NOT PERMITTED.
      N=1
      C=CMPLX(0.,0.)
      DO 1 I=1,N
      CS=CMPLX(COS(CA*I*PE(I)),-SIN(CA*I*PE(I)))
      IF (LMODE .EQ. 2) GO TO 2
      C=C+SINC(.5*AA(I)*CA/PI)*ETA**I*SQRT(EL1(I))*CS
      GO TO 3
 2    CONTINUE
      C=C+SINC(2.*AA(I)/(PE(I)*(3.-ETA)))*
     XSINC((CA*PE(I)*.5/PI)   -.25 *(3.+ETA))*ETA**I*SQRT(EL1(I))*CS
 3    CONTINUE
 1    CONTINUE
      GAY=CABS(C)
      RETURN
      END

      FUNCTION SINC(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
      PI=3.14159265
      SINC=(SIN(PI*CA))/(PI*CA)
      RETURN
      END

      FUNCTION FT1(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A
      FTT     =EXP(-B*CA*D)*(R1(CA)*EXP(CA*G)-R2(CA)*EXP(-CA*G))
     X*S*T1*(CSCH(CA*T1))**2
      FTT2=
     X-S*D*EXP(-B*CA*D)*((COTH(CA*T1)+1.)*R1(CA)*EXP(CA G)
     X+(COTH(CA*T1)-1.)*R2(CA)*EXP(-CA*G))
      FTT3=
     X+2.*B*S*D*EXP(-2.*B*CA*D)*((COTH(CA*T1)+1.)*(1.-AL2)
     X*EXP(CA*G)-(COTH(CA*T1)-1.)*(1.+AL2)*EXP(-CA*G))
      FTT5=
     X+S*EL*(AL1+AL2)*(SECH(CA*EL)**2)/(AL1-TANH(CA*EL))**2
      FTT6=
     X ((COTH(CA*T1)-1.)*(1.-AL1)*EXP(-CA*G)-(COTH(CA*T1)+1.)
     X*(1.+AL1)*EXP(CA*G))
      FTT4=FTT5+FTT6
      FT1=.5*(FTT+FTT2+FTT3+FTT4)
      RETURN
      END
```

```
      SUBROUTINE HTRAN(R,X,N,FBEG,FEND)
      DIMENSION R(3),X(3)
      PI=3.14159265359
      FDEL=(FEND-FBEG)/(N-1)
      F=FBEG+.5*FDEL
      INC=MOD(N,2)
      NI=N+INC-1
       NM1=N-1
      NIM2=NI-2
      DO 33 I=1,NM1
      X(I)=0.
      IF (I .EQ. 1) RX=(3.*R(1)+6.*R(2)-R(3))/8.
      IF (I .EQ. NM1) RX=(-R(N-2)+6.*R(NM1)+3.*R (N))/8.
      IF (I .EQ. 1 .OR. I .EQ. NM1) GO TO 20
      RX=(-R(I-1)+9.*R(I)+9.*R(I+1)-R(I+2))/16.
   20 CONTINUE
      FI=FBEG
      DO 28 IP=1,NIM2,2
      X(I)=X(I)+4.*(R(IP+1)-RX)/(( FI+FDEL)**2-F**2)
     X          +2.*(R(IP  )-RX)/(   FI        **2-F**2)
      FI=FI+2.*FDEL
   28 CONTINUE
      FEN=FEND
      IF(INC .EQ. 0 ) FEN=FEND-FDEL
      X(I)=X(I)+(R(NI)-RX)/(FEN**2-F**2)
     X          -(R(1  )-RX)/(FBEG**2-F**2)
      X(I)=FDEL/3.*X(I)
      IF(INC .EQ.1) GO TO 32
      X(I)=X(I)+.5*FDEL*((R(NI)-RX)/(FEN**2-F* 2)
     X          +(R(N)-RX)/(FEND**2-F**2))
   32 X(I)=2./PI*F*X(I)+RX/PI*ALOG
     X ((1.-F/FEND)/(1.+F/FEND)*(F+FBEG)/(F-FBEG))
      F=F+FDEL
   33 CONTINUE
      NM2=N-2
      X1=(15.*X(1)-10.*X(2)+3.*X(3))/8.
       X2=(3.*X(1)+6.*X(2)-X(3))/8.
      DO  31  I=3,NM2
      X3=(-X(I-2)+9.*X(I-1)+9.*X(I)-X(I+1))/16.
      X(I-2)=X1
      X1=X2
      X2=X3
   31 CONTINUE
      X(N)=(15.*X(NM1)-10.*X(NM2)+3.*X(N-3))/8.
      X(N-1)=(3.*X(NM1)+6.*X(NM2)-X(N-3))/8.
      X(N-2)=X2
      X(N-3)=X1
      RETURN
      END


      FUNCTION GF(CA)
      COMMON EL,AL1,AL2,B,D,T1,G,S,ETA,EN,P,AY,A,EL1(40),PE(40),AA(40)
      GF    =ABS(GAY(CA) *EXP(-B*CA*D)/FT1(CA))
      RETURN
      END
```

C. Generalized Dispersion Relation

Another program has been implemented on the CDC 6600 at Hanscom AFB, Ma which solves the dispersion relation problem for surface waves including any arbitrary orientation of the biasing field. Computer print-outs and plots of wave number, wave length and group delay, as functions of frequency, for both + and - solutions, are provided by the program.

The input cards to this program are:

Card 1 - H_o, t_1, d, θ, ℓ, ϕ

These six quantities, separated by commas, are supplied here. The lengths are in meters and the angles are in degrees.

Card 2 - first f, Δf, number of frequency values

Here the user is to provide the first frequency value, the frequency increment and the number of frequency values to be considered, all separated by commas. The maximum number of frequency values permitted is currently 500. Although the program could compute the frequency range itself as in the other programs it was left for input to provide flexibility.

Card 3 - heading

Card 4 - heading

Two heading cards for the graphs are here required. Columns 1-70 may be used.

The listing of the entire program, excluding the standard control cards, now follows.

```
C    PHI=9  DEG    THETA=90 DEG  ----------    SURFACE WAVES
      PROGRAM VOLM(INPUT,OUTPUT)
      DIMENSION PROGID(3)
      DIMENSION F(501),FP(501),FM(501),CAP(501),CAM(501)
      DIMENSION HEAD1(7),HEAD2(7)
     X ,VGP(501),VGM(501),ELAP(501),ELAM(501)
      COMMON D,EL,T1,S,C,AL1,AL2
      READ *,H,T1,D,THET,EL,PHI
      READ *,FBEG,FDEL,NF
      READ 100,HEAD1
      READ 100,HEAD2
      PRINT 60
      PRINT 61,H,T1,D,THET,EL,PHI
      PRINT 60
      DATA PROGID/8HSETHARES,4H2587,10HJ.WEINBERG/
      CALL PLTID3(PROGID,100.,12.,1.)
      DO 40 I=1,NF
   40 F(I)=FBEG+(I-1)*FDEL
      PI=3.14159265
      THET=THET*PI/180.
      PHI=PHI*PI/180.
      FM=1750.
      GAM=2.8
      TU=GAM**2*H*FM
      K=1
      I=1
      J=1
   50 FF=F(K)
      TD=(GAM*H)**2-FF**2
      T2=GAM*FM*FF
      UYY=TU/TD*(SIN(THET))**2+1.
      UXX=TU/TD*((SIN(THET)*SIN(PHI))**2+(COS(THET))**2)+1.
      UXYYY=-2.*TU/TD*COS(THET)*COS(PHI)*SIN(THET)
      UXYYYI=T2/TD*SIN(THET)*SIN(PHI)
      TEM=UXYYY**2-4.*UXX*UYY
      TEM=-TEM
       L=2
      IF (TEM .LE. 0.) PRINT *,"  NEGATIVE SQUARE ROOT"
      IF (TEM .LE. 0.) GO TO 35
      C=SQRT(TEM) .5/UYY
      L=1
   70 IF (L .EQ. 2) GO TO 2
    1 S=1.
      GO TO 3
    2 S=-1.
    3 CONTINUE
      AL2=C*UYY+S UXYYYI
      AL1=C*UYY-S UXYYYI
       IF (J .GT. 1) GO TO 53
      TO=(AL2+1.)/(AL1-1.)
      CAO=ALOG((AL2-1.)/(TO*(AL1+1.)))/2./C/D
      IF (CAO .LT. 0.) CAO=100.
   53 CONTINUE
      IF (I .EQ. 1) GO TO 51
        IF (J .EQ. 1) GO TO 51
      IF(L .EQ. 1) CAO=CAP(I-1)
      IF(L .EQ. 2) CAO=CAM(J-1)
```

```
51    M=1
 5    DEL=.02*CAO
      CAOP=CAO+DEL
      CAOM=CAO-DEL
      CAOD=CAO*D*C
      CAOD=ABS(CAOD)
      IF(CAOD .GT. 650.) GO TO 35
      FTCO=FT(CAO)
      FTCP=FT(CAOP)
      FTCM=FT(CAOM)
      CA1=CAO-2.*DEL*FTCO/(FTCP-FTCM)
      IF(ABS(CA1) .GT. 1.E7) GO TO 35
      CA1D=CA1*D*C
      CA1D=ABS(CA1D)
      IF(CA1D .GT. 650.) GO TO 35
      FTC1=FT(CA1)
C     PRINT *,CAO,FTCO,CA1,FTC1
      IF (ABS((CA1-CAO)/CAO) .LT.  .001) GO TO 10
      CAO=CA1
      M=M+1
      IF(M .GT.10) GO TO 35
      GO TO 5
10    IF (L .EQ. 2) GO TO 20
      CA=CA1
      IF (ABS(FTC1) .GT. 1.) GO TO 35
      IF (CA .LT. 0.) GO TO 35
      FP(I)=EF
      CAP(I)=CA
      I=I+1
C     PRINT *,"CA= ",CA,"F= ",EF
      L=2
      GO TO 30
20    CA=CA1
      IF (ABS(FTC1) .GT. 1.) GO TO 35
      IF (CA .LT. 0.) GO TO 35
      FM(J)=EF
      CAM(J)=CA
      J=J+1
C     PRINT *,"CA= ",CA,"F= ",EF
       IF (J .EQ. I) GO TO 15
      IF (J .GT. I) GO TO 31
      I=J-1
      K=K-1
31    J=J-1
15    K=K+1
      IF (K .LE. NF) GO TO 50
      PRINT 60
      I1=I-1
      J1=J-1
      GO TO 24
35    PRINT *,"ITERATION DOES NOT CONVERGE.F= ",EF," S= ",S
      IF (L .EQ. 2) GO TO 15
      L=2
      GO TO 2
24    CONTINUE
      PRINT 63,(FP(LL),CAP(LL),LL=1,I1,5)
      PRINT 64,(FM(LL),CAM(LL),LL=1,J1,5)
```

```
      PRINT 6
      DO 11 I=1,I1
   11 ELAP(I)=2./PI/CAP(I)*1.E6
      DO 12 J=1,J1
   12 ELAM(J)=2.*PI/CAM(J)*1.E6
C     PRINT 65,(FP(LL),ELAP(LL),LL=1,I1,5)
C     PRINT 66,(FM(LL),ELAM(LL),LL=1,J1,5)
      DO 21 I=1,I1
      IF (I .EQ. 1) VGP(I)=5./PI*(CAP(2)-CAP(1))/FDEL
      IF (I .EQ. I1) VGP(I)=5./PI*(CAP(I1)-CAP(I1-1))/FDEL
      IF (I .NE. 1 .AND. I .NE. I1) VGP(I)=
     X5./PI*(CAP(I+1)-CAP(I-1))/FDEL*.5
   21 CONTINUE
C     PRINT 67,(FP(I),VGP(I),I=1,I1,10)
      DO 22 J=1,J1
      IF (J .EQ. 1) VGM(J)=5./PI*(CAM(2)-CAM(1))/FDEL
      IF (J .EQ. J1) VGM(J)=5./PI*(CAM(J1)-CAM(J1-1))/FDEL
      IF (J .NE. 1 .AND. J .NE. J1) VGM(J)=
     X5./PI*(CAM(J+1)-CAM(J-1))/FDEL*.5
   22 CONTINUE
C     PRINT 68,(FM(J),VGM(J),J=1,J1,10)
      YMIN=2500.
      DY=100.
      XMIN=2100.
      DX=10.
      YMIN=0.
      DY=5000.
      DO 13 I=1,I1
      IF (CAP(I) .GT. 500000.) CAP(I)=500000.
      IF (ELAP(I) .GT. 1000.  ) ELAP(I)=1000.
      VGP(I)=ABS(VGP(I))
   13 IF (VGP(I) .GT. 1000.) VGP(I)=1000.
      DO 14 J=1,J1
      IF (CAM(J) .GT. 500000.) CAM(J)=500000.
      IF (ELAM(J) .GT. 1000.  ) ELAM(J)=1000.
      VGM(J)=ABS(VGM(J))
   14 IF (VGM(J) .GT. 1000.) VGM(J)=1000.
      X=10.
      YY=10.
      XX=10.
      CALL PLOT(1.5,0.,-3)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL AXIS(0.,0.,26HWAVE NUMBER K(+) (1/METER),26,Y,90.,YMIN,DY,YY)
      CALL AXIS(0.,0.,15HFREQUENCY (MHZ),-15,X  ,0.,XMIN,DX,YY)
      CALL LINE (FM,CAM,
     X                   J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT (16.,0.,-3)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL AXIS(0.,0.,26HWAVE NUMBER K(-) (1/METER),26,X,90.,YMIN,DY,YY)
      CALL AXIS(0.,0.,15HFREQUENCY (MHZ),-15,X  ,0.,XMIN,DX,YY)
      CALL LINE(FP,CAP,
     Y                   I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      DY=100.
      CALL PLOT (17.,0.,-3)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
```

```
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL AXIS(0.,0.,24HWAVELENGTH (+) (MICRONS),24,XX, 0.,YMIN,DY,YY)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,YY)
      CALL LINE (FM,FLAM,J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT (13.,0.,-3)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL AXIS(0.,0.,24HWAVELENGTH (-) (MICRONS),24,XX,90.,YMIN,DY,YY)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,YY)
      CALL LINE (FP,FLAP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT(13.,0.,-3)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL AXIS(0.,0.,
     X              25HGROUP DELAY/CM (+) (NSEC),25,XX ,90.,YMIN,DY,YY)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,YY)
      CALL LINE(FM,VGM,J1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL PLOT(13.,0.,-3)
      CALL SYMBOL(.5,9.6,.1,HEAD1,0,70)
      CALL SYMBOL(.5,9.4,.1,HEAD2,0,70)
      CALL AXIS(0.,0.,
     X              25HGROUP DELAY/CM (-) (NSEC),25,XX , 0.,YMIN,DY,YY)
      CALL AXIS (0.,0.,15HFREQUENCY (MHZ),-15,XX ,0.,XMIN,DX,YY)
      CALL LINE(FP,VGP,I1,1,0,1,XMIN,DX,YMIN,DY,.08)
      CALL ENDPLT
      STOP
 60   FORMAT(1H1)
 61   FORMAT(5X," H= ",E15.7/5X," T1= ",E15.7/5X," D= ",E15.7/
     X" THETA=",E15.7/5X," L= ",E15.7/5X,"PHI= ",E15.7)
 62   FORMAT(//10(8F15.5/))
 63   FORMAT(///50X,"S=1"//(10X,"F= ",E15.7,10X,"K  (-)=  ",E15.7/))
 64   FORMAT(///50X,"S=-1"//(10X,"F= ",E15.7,10X,"K  (+) = ",E15.7/))
 65   FORMAT(///50X,"S=1"//(10X,"F= ",E15.7,10X,"LAM(-)=  ",E15.7/))
 66   FORMAT(///50X,"S=-1"//(10X,"F= ",E15.7,10X,"LAM(+) = ",E15.7/))
 67   FORMAT("    F=  ",E15.7,"    GROUP DELAY (-) =  ",E15.7)
 85   FORMAT(/(10X," F= ",E15.7,10X,"GROUP DELAY (+) = ",E15.7/))
100   FORMAT(7A10)
      END
```

```
      FUNCTION COTH(CA)
      COMMON D,EL,T1,S,C,AL1,AL2
      IF (CA .GT. 17.3) GO TO 3
      IF (CA .LT. -17.3) GO TO 4
      COTH    =1./TANH(CA)
      GO TO 2
 3      COTH=1.
      GO TO 2
 4    COTH=-1.
 2     CONTINUE
      RETURN
      END


      FUNCTION T(CA)
      COMMON D,EL,T1,S,C,AL1,AL2
      CAEL=CA*EL
      IF (CAEL .GT. 17.3) GO TO 43
      IF (CAEL .LT. -17.3) GO TO 44
      T=(AL2+TANH(CAEL))/(AL1-TANH(CAEL))
      GO TO 45
 43   T=(AL2+1.)/(AL1-1.)
      GO TO 45
 44   T=(AL2-1.)/(AL1+1.)
 45   CONTINUE
      RETURN
       END


      FUNCTION FT(CA)
      COMMON D,EL,T1,S,C,AL1,AL2
      FT=EXP(    C*CA*D)*T(CA)*(AL1*COTH(CA*T1)+1.)
     X    +(1.-AL2*COTH(CA*T1))*EXP(-C*CA*D)
      RETURN
      END
```

COMPLETED CASES

In this section there are presented graphical results produced by the computer programs for various cases.

In figures 2-12 are the results of the basic theory for one set of parameters, omitting conduction loss. Non-apodized independent conductors are considered. Graphs are presented for wave number (plus wave), group delay (plus wave), wave number (minus wave), group delay (minus wave), normalized dispersion (plus wave), radiation resistance (plus wave), radiation resistance (minus wave), total radiation resistance, total radiation reactance, negative of insertion loss (plus wave) and negative of insertion loss (minus wave).

In figures 13-16 are the results of the microstrip model for the same set of parameters as above. Presented are graphs of input resistance, input reactance, negative of insertion loss (plus wave) and negative of insertion loss (minus wave).

A second set of parameters is considered in Figures 17-28. The basic theory is employed for non-apodized independent conductors. There are presented graphs for radiation resistance (minus wave), radiation resistance (plus wave), total radiation resistance, total radiation reactance, negative of insertion loss (minus wave) and negative of insertion loss (plus wave). Results are obtained for N=1, N=2, N=8 and N=100.

Another set of parameters is considered in all of the figures 29-46.

In figures 29-31 the radiation resistance (minus wave) is presented for the cases of no apodization, apodization in strip width

and apodization in center to center spacing. The basic theory for independent conductors is here considered.

In figures 32-34 there are presented graphs for radiation resistance (minus wave) for the cases of no apodization, apodization in strip width and apodization in center to center spacing. Here the basic theory for normal modes has been considered.

Figure 35 presents the radiation resistance (minus wave) and radiation resistance (plus wave) for the basic theory with independent conductors.

Figure 36 presents the radiation resistance (minus wave) and radiation resistance (plus wave) as above, with no ground planes.

In figures 37-38 are presented the radiation resistance (minus wave) and radiation resistance (plus wave) for the basic theory with normal modes; for the fundamental mode and for n=3.

In figure 39 the radiation resistance (minus wave), radiation resistance (plus wave) and total radiation resistance are presented for the basic theory with independent conductors and no ground planes, for N=1.

In figure 40 the radiation resistance (minus wave) and radiation resistance (plus wave) for the case as above, with N=3, are presented.

In figure 41 the radiation resistances (plus wave) are presented for the basic theory with independent conductors, for N=1, N=2, N=3 and N=4.

In figure 42 the radiation resistances (plus wave) for the basic theory with independent conductors, for N=4, are presented for three different gap thicknesses.

In figures 43-44 there are presented the radiation resistance (plus wave) and radiation resistance (minus wave) for the basic theory with normal modes, for N=32.

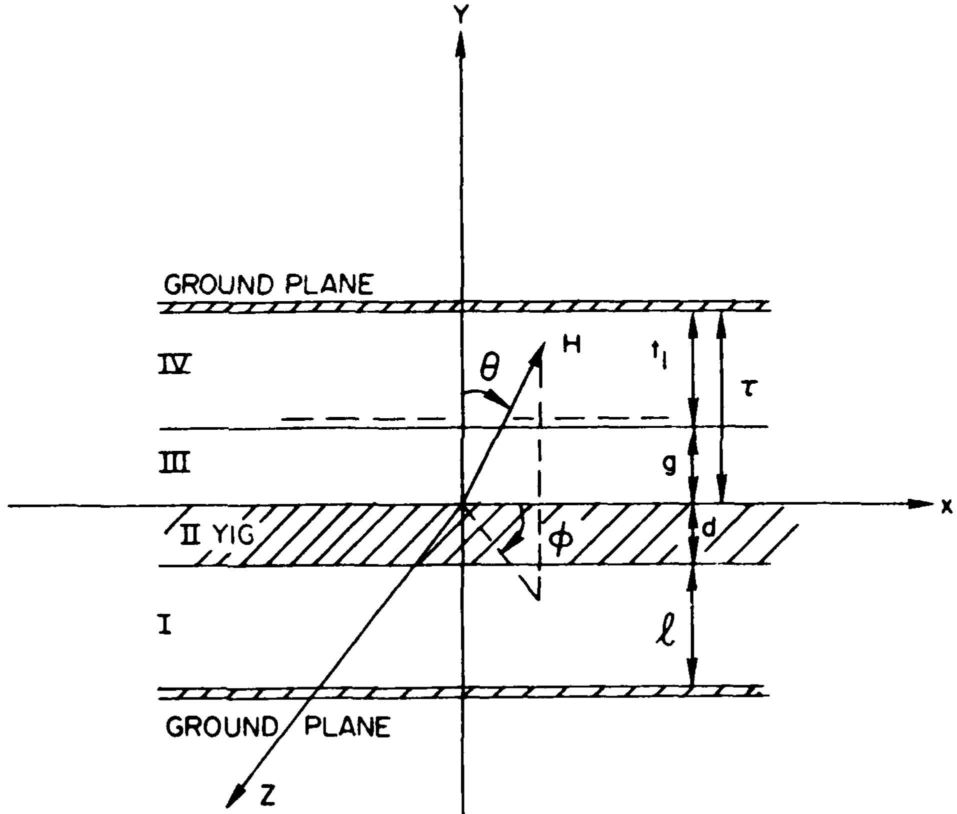
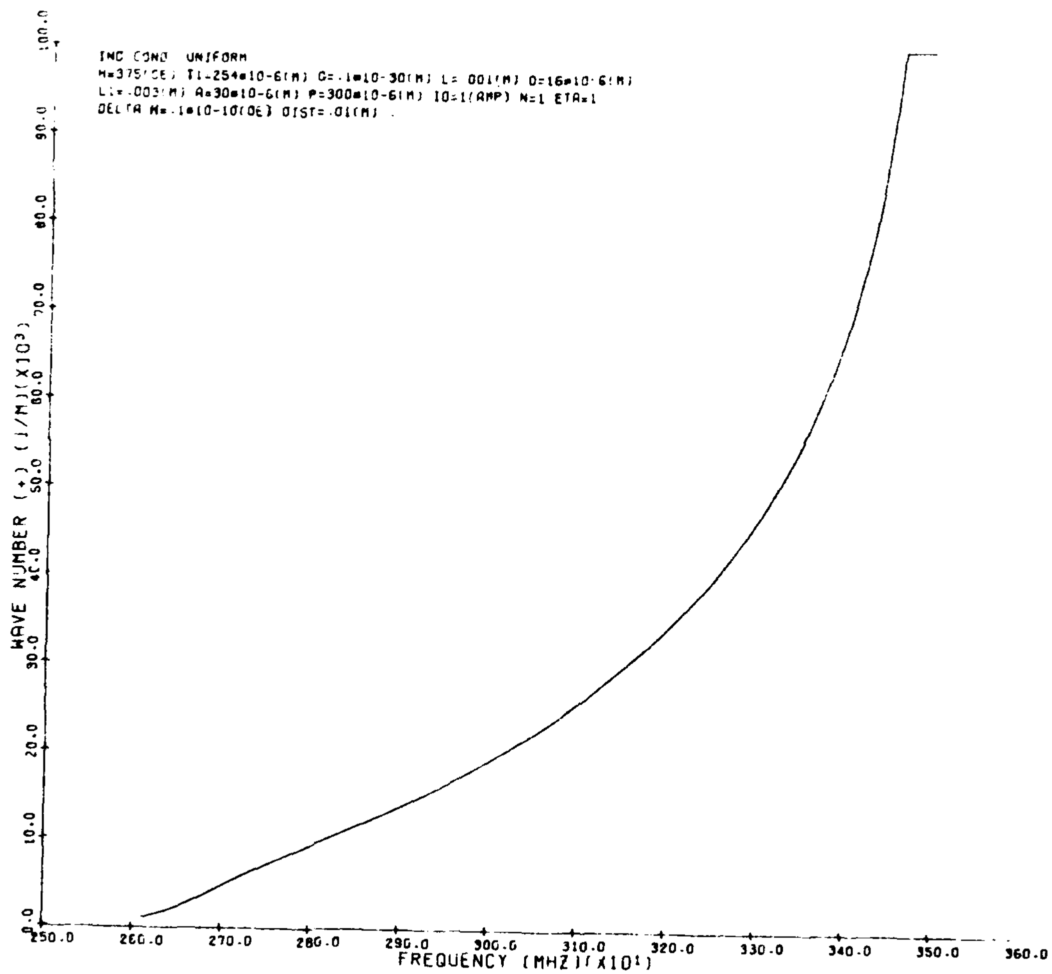
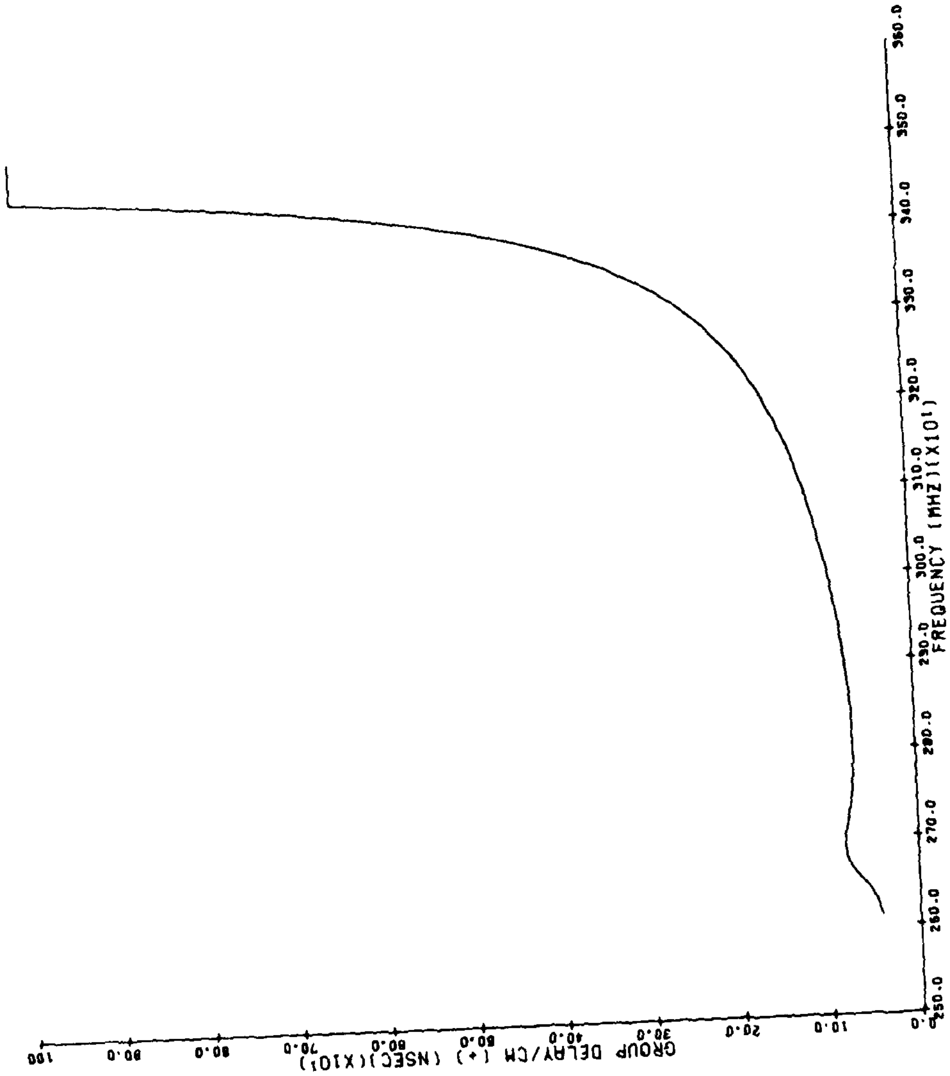


Figure 1



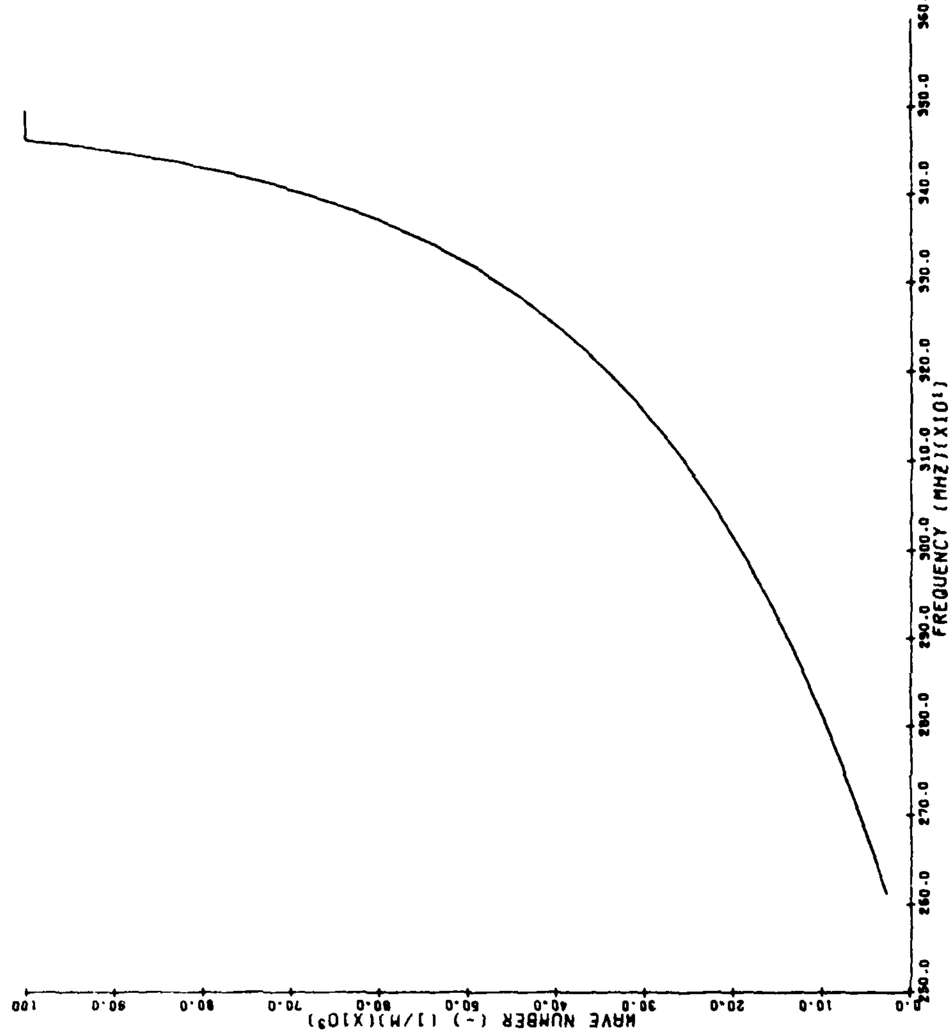
INC COND UNIFORM
H=375(OE) TI=.254*10-6(M) G=.1*10-30(M) L=.001(M) D=16*10-6(M)
LI=.003(M) A=30*10-6(M) P=300*10-6(M) IO=1(AMP) N=1 ETA=1
DELTA H=.1*10-10(OE) DIST=.01(M)
WAVE NUMBER (+) (1/M)(X10³)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
FREQUENCY (MHZ)(X10¹)

Figure 2



FREQUENCY (MHZ)(X10¹)
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
GROUP DELAY/CM (+) (NSEC)(X10¹)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100

Figure 3



FREQUENCY (MHZ)(X10¹)
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
WAVE NUMBER (-) (1/M)(X10³)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100

Figure 4

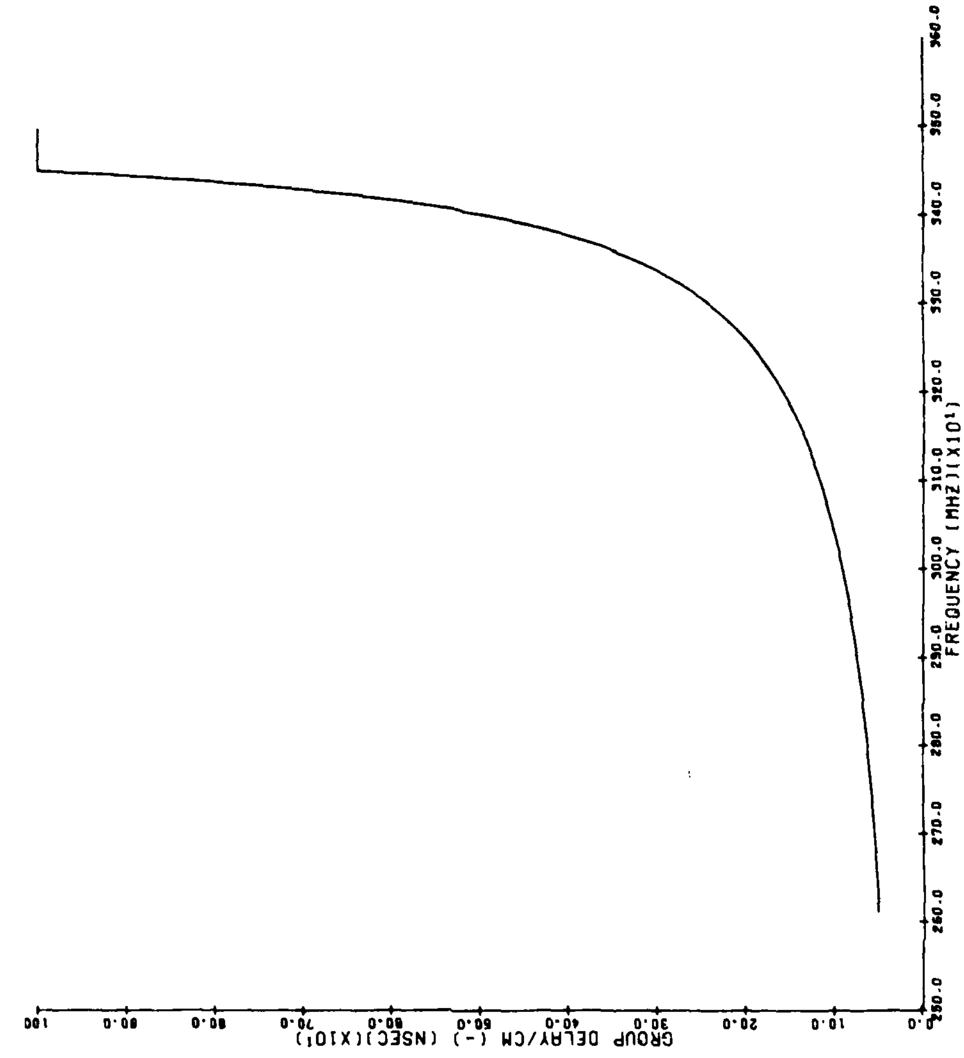

FREQUENCY (MHZ)(X10¹)
GROUP DELAY/CM (-) (NSEC)(X10¹)
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100

Figure 5

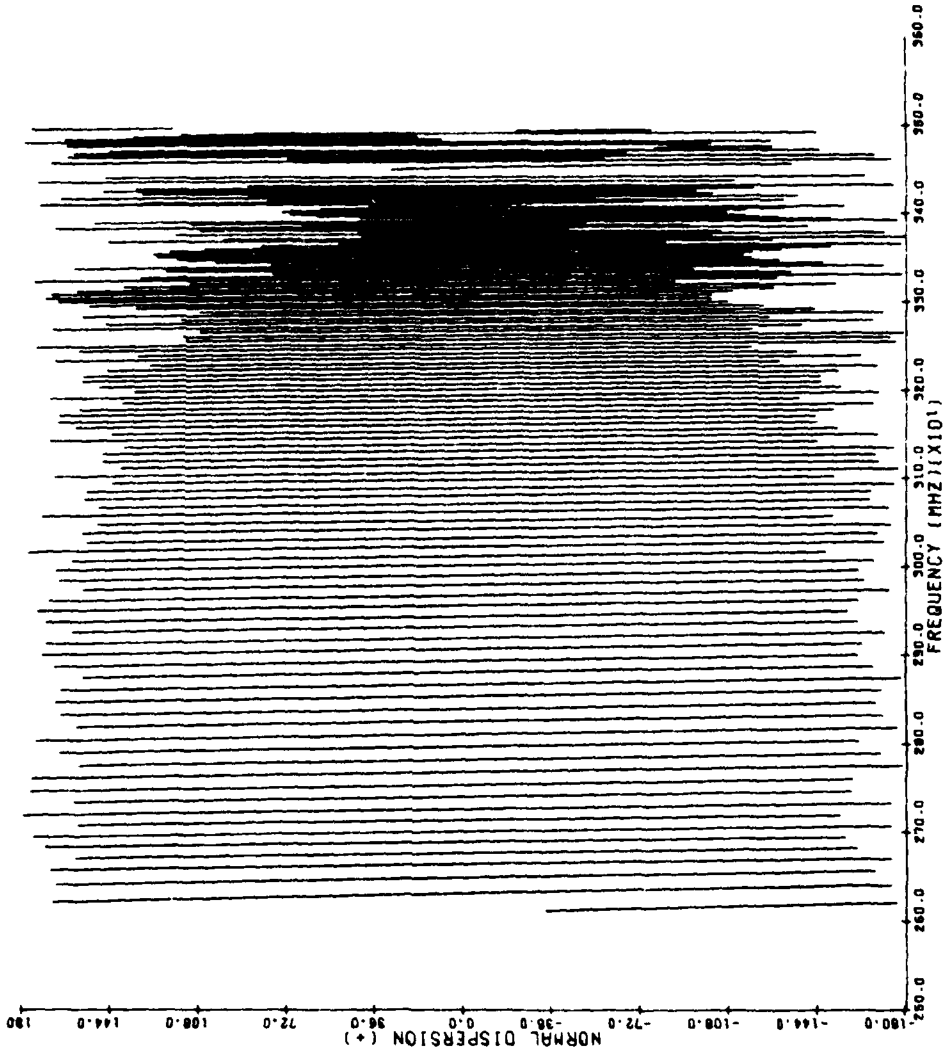


Figure 6

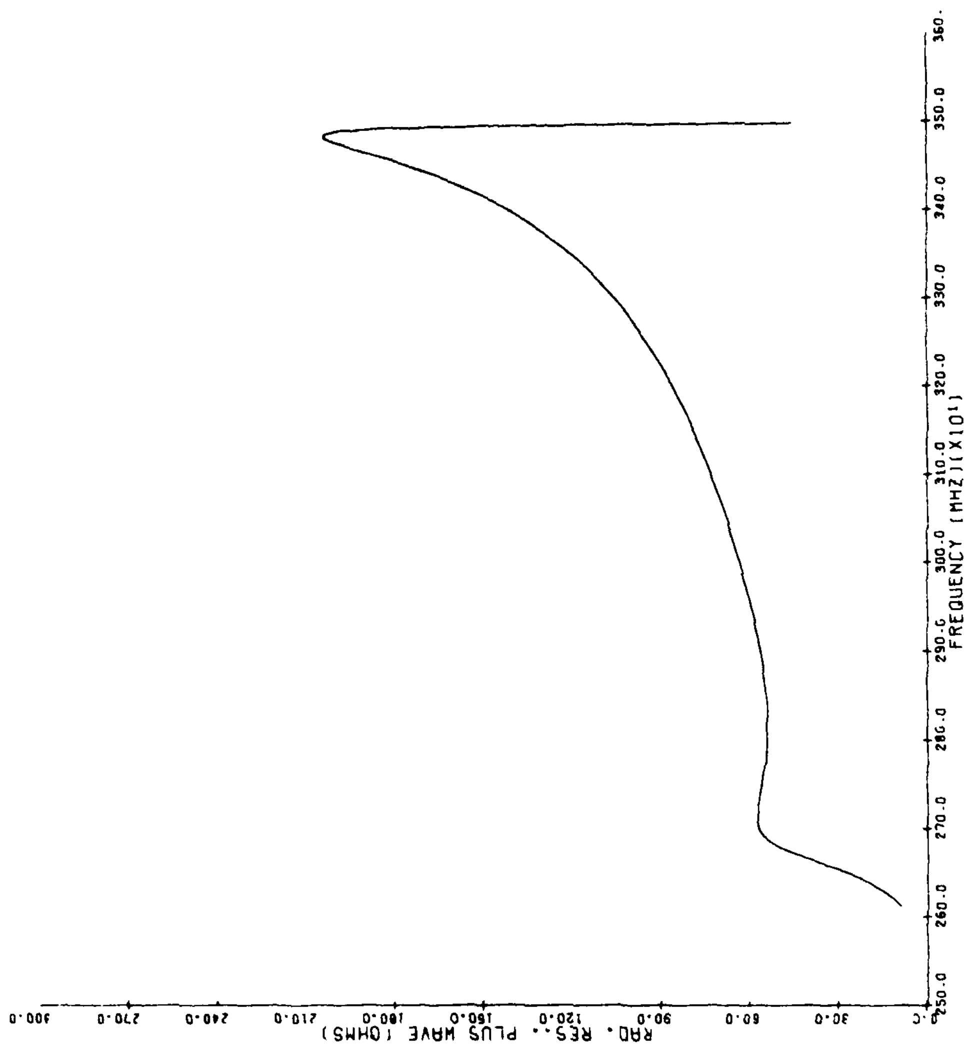

FREQUENCY (MHZ)(X10^1)
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.
RAD. RES., PLUS WAVE (OHMS)
0.0
30.0
60.0
90.0
120.0
150.0
180.0
210.0
240.0
270.0
300.0

Figure 7

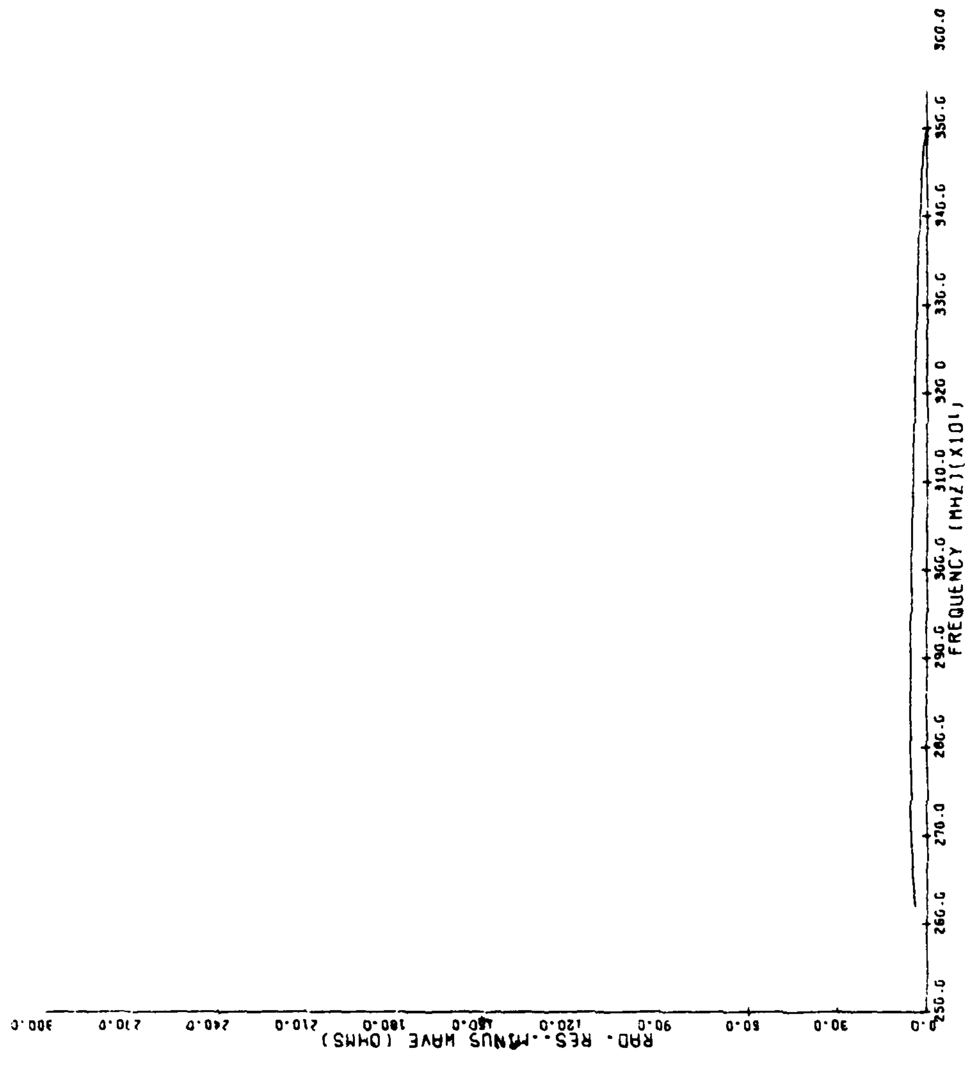

250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
FREQUENCY (MHZ)(X10¹)
0.0
30.0
60.0
90.0
120.0
150.0
180.0
210.0
240.0
270.0
300.0
RAD. RES.-MINUS WAVE (OHMS)

Figure 8

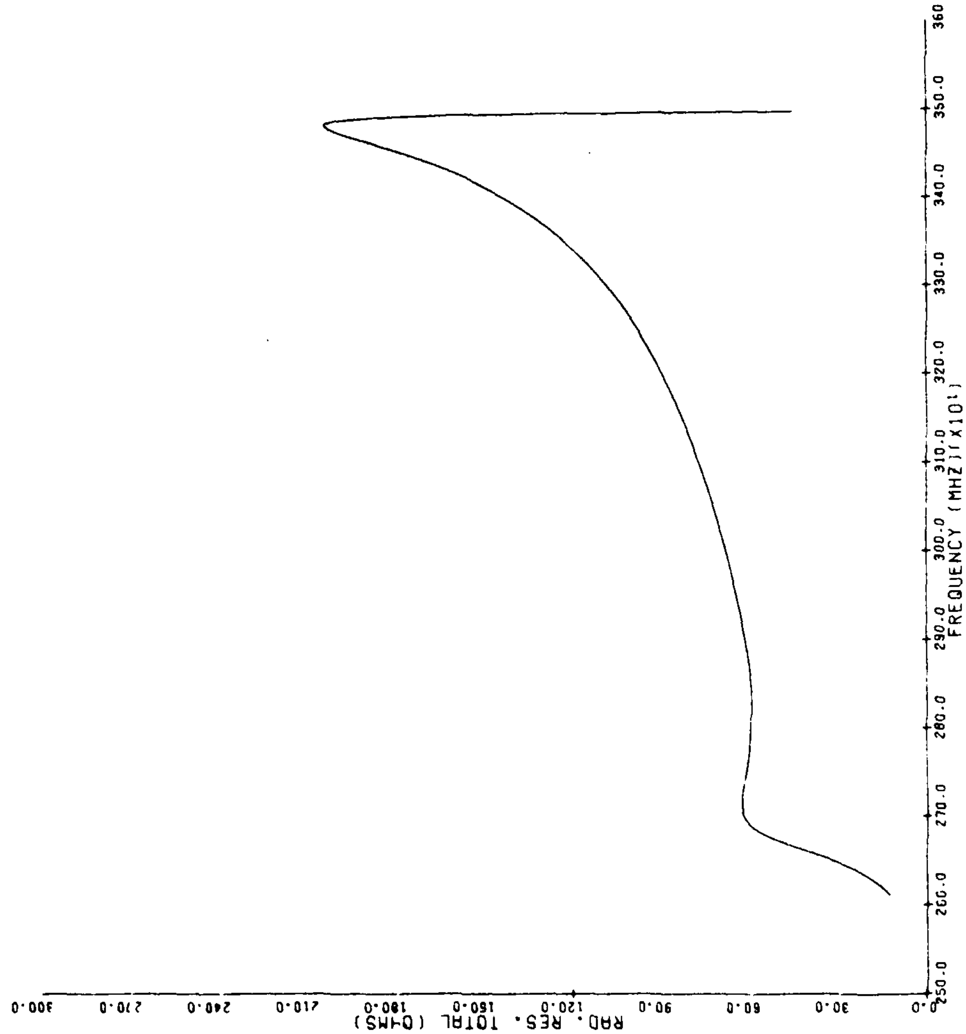

RAD. RES. TOTAL (OHMS)
0.0
30.0
60.0
90.0
120.0
150.0
180.0
210.0
240.0
270.0
300.0
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
FREQUENCY (MHZ)(X10¹)

Figure 9

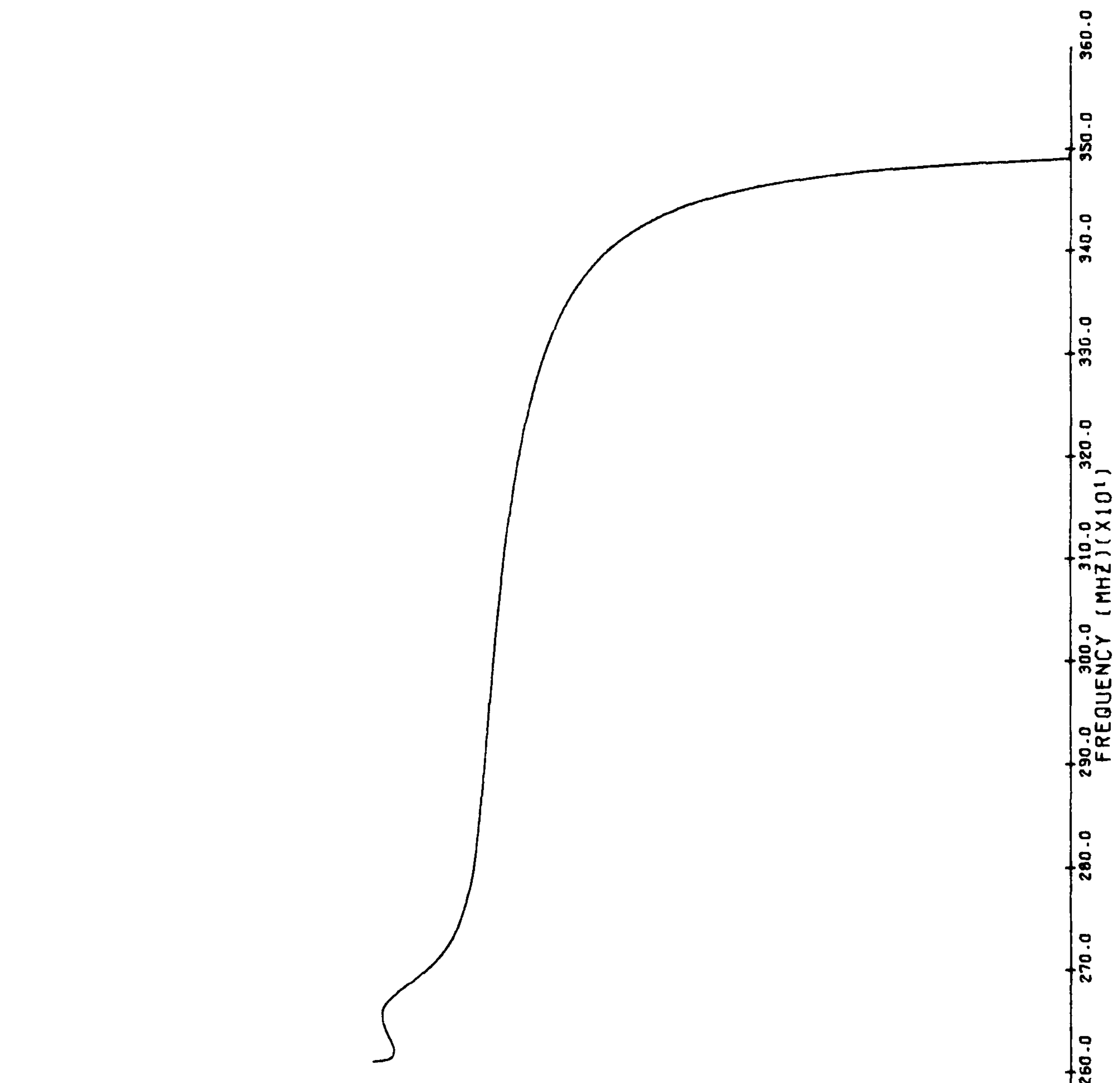
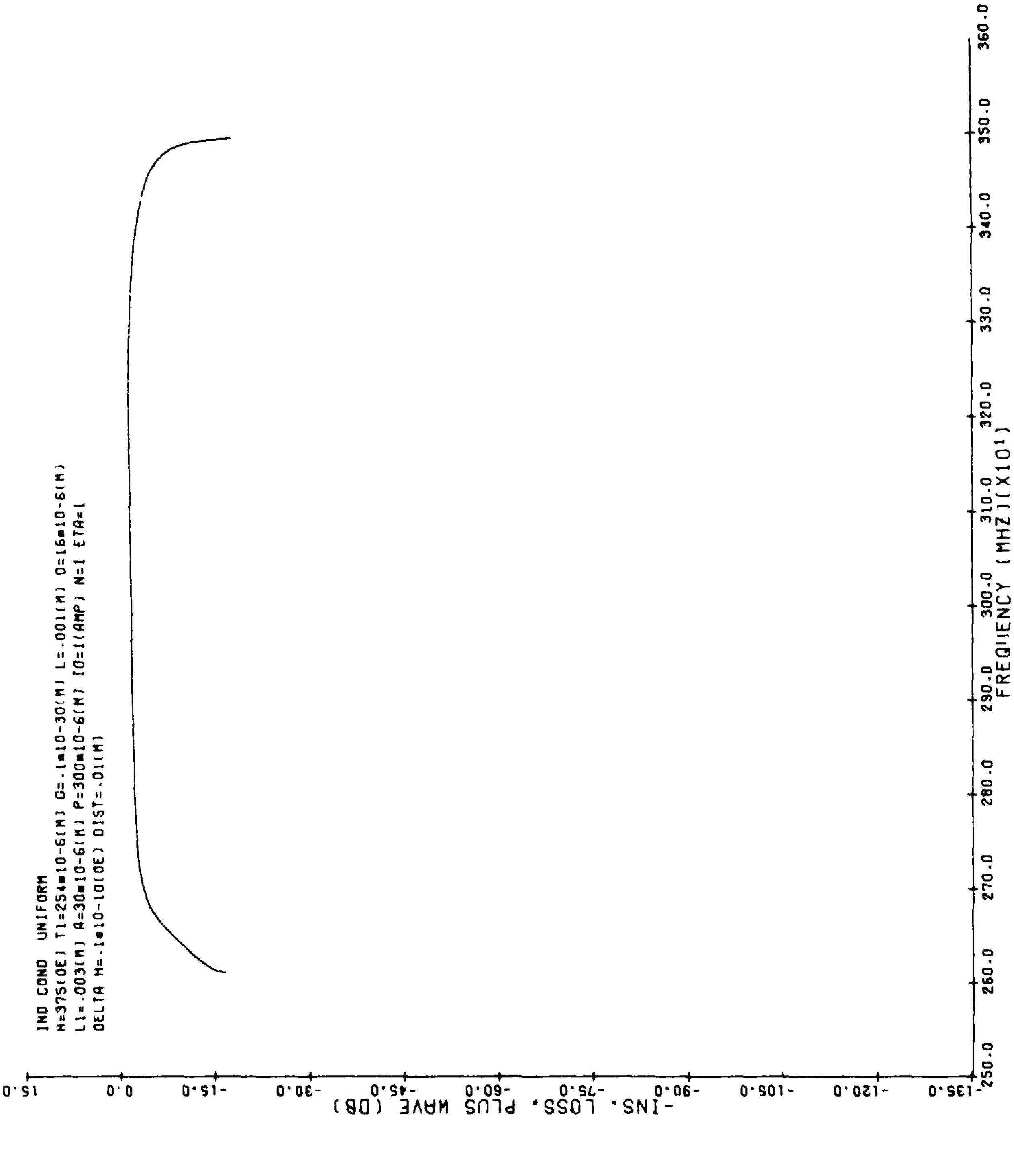

FREQUENCY (MHZ)(X10^1)
RAD. REAC TOTAL (OHMS)
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0

Figure 10



IND COND UNIFORM
H=375(OE) T1=254*10-6(M) G=.1*10-30(M) L=.001(M) D=16*10-6(M)
L1=.003(M) A=30*10-6(M) P=300*10-6(M) IO=1(AMP) N=1 ETA=1
DELTA H=.1*10-10(OE) DIST=.01(M)
-INS. LOSS. PLUS WAVE (DB)
15.0
0.0
-15.0
-30.0
-45.0
-60.0
-75.0
-90.0
-105.0
-120.0
-135.0
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
FREQUENCY (MHZ)(X10¹)

Figure 11

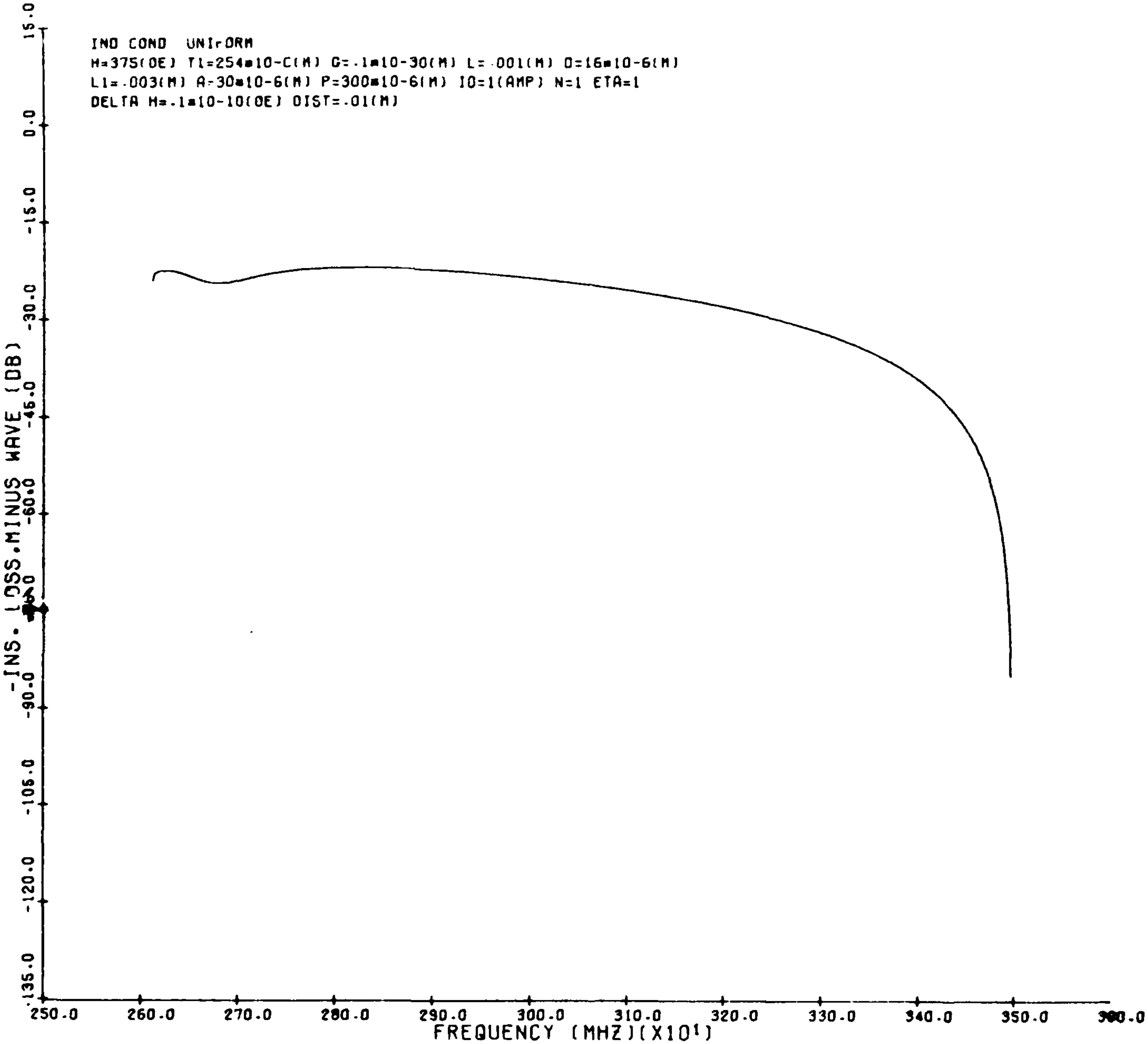

IND COND UNIFORM
H=375(OE) T1=254*10-C(M) G=.1*10-30(M) L=.001(M) D=16*10-6(M)
L1=.003(M) A=30*10-6(M) P=300*10-6(M) IO=1(AMP) N=1 ETA=1
DELTA H=.1*10-10(OE) DIST=.01(M)
-INS. LOSS.MINUS WAVE (DB)
15.0
0.0
-15.0
-30.0
-45.0
-60.0
-90.0
-105.0
-120.0
-135.0
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
FREQUENCY (MHZ)(X10¹)

Figure 12

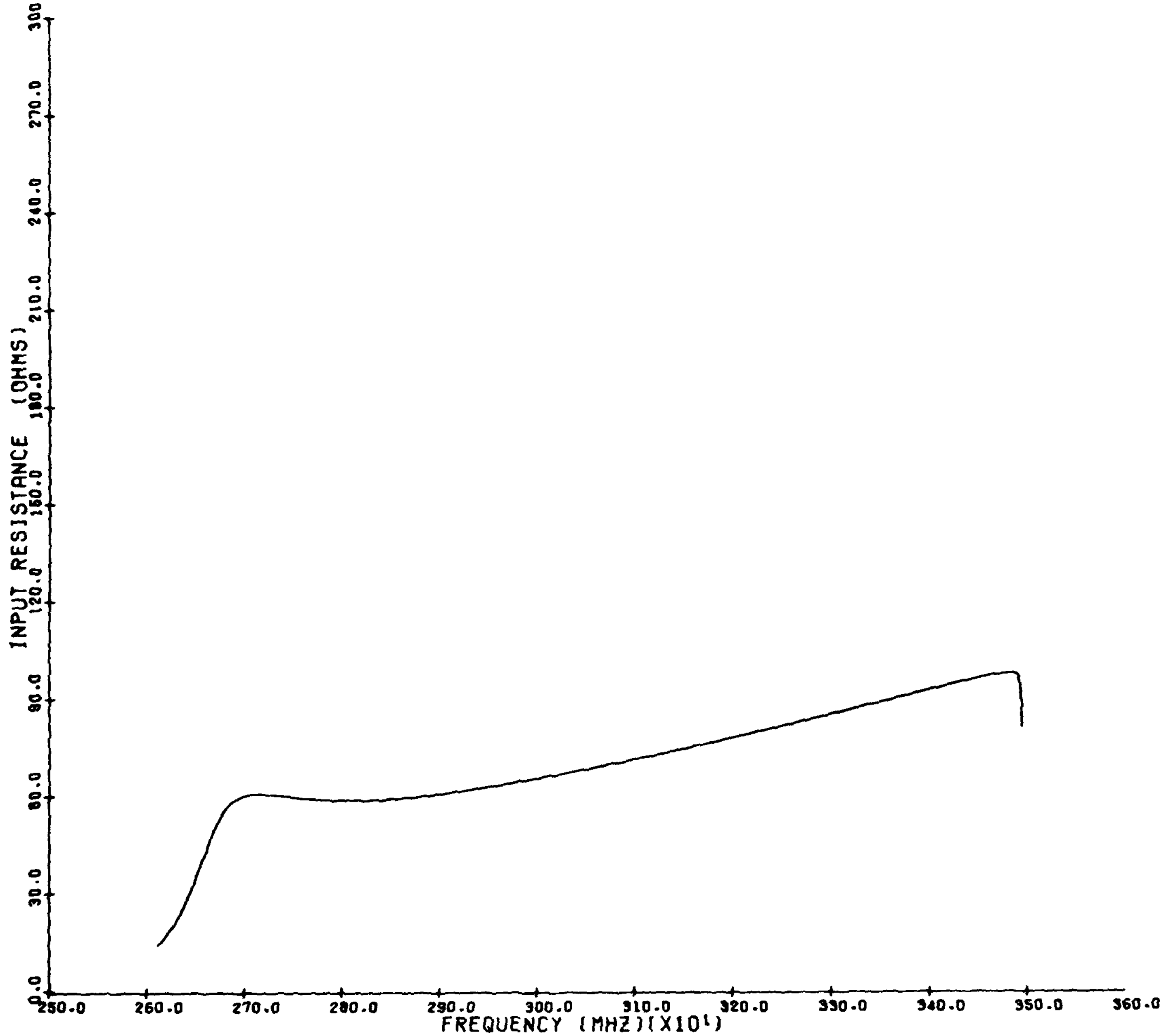
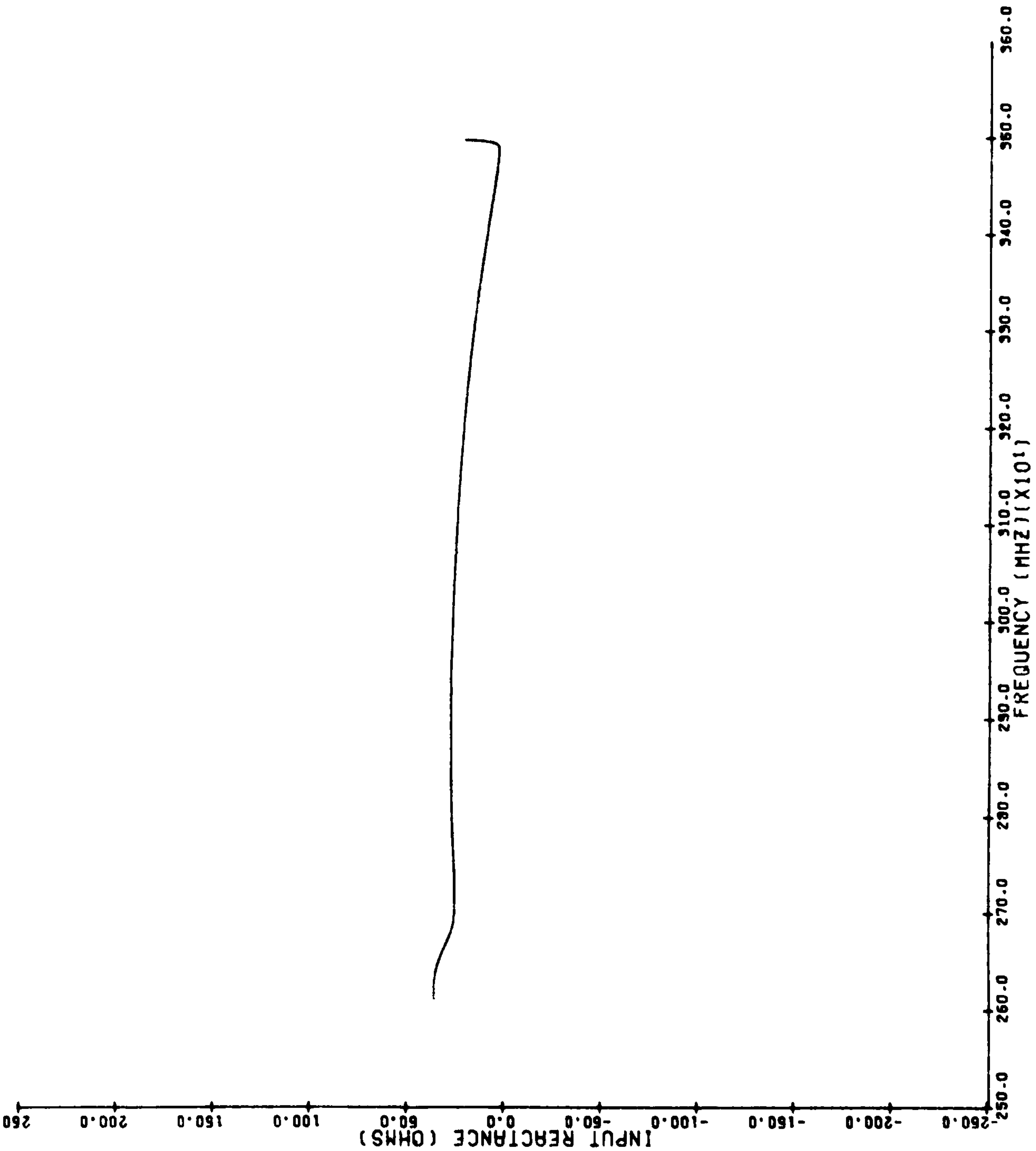
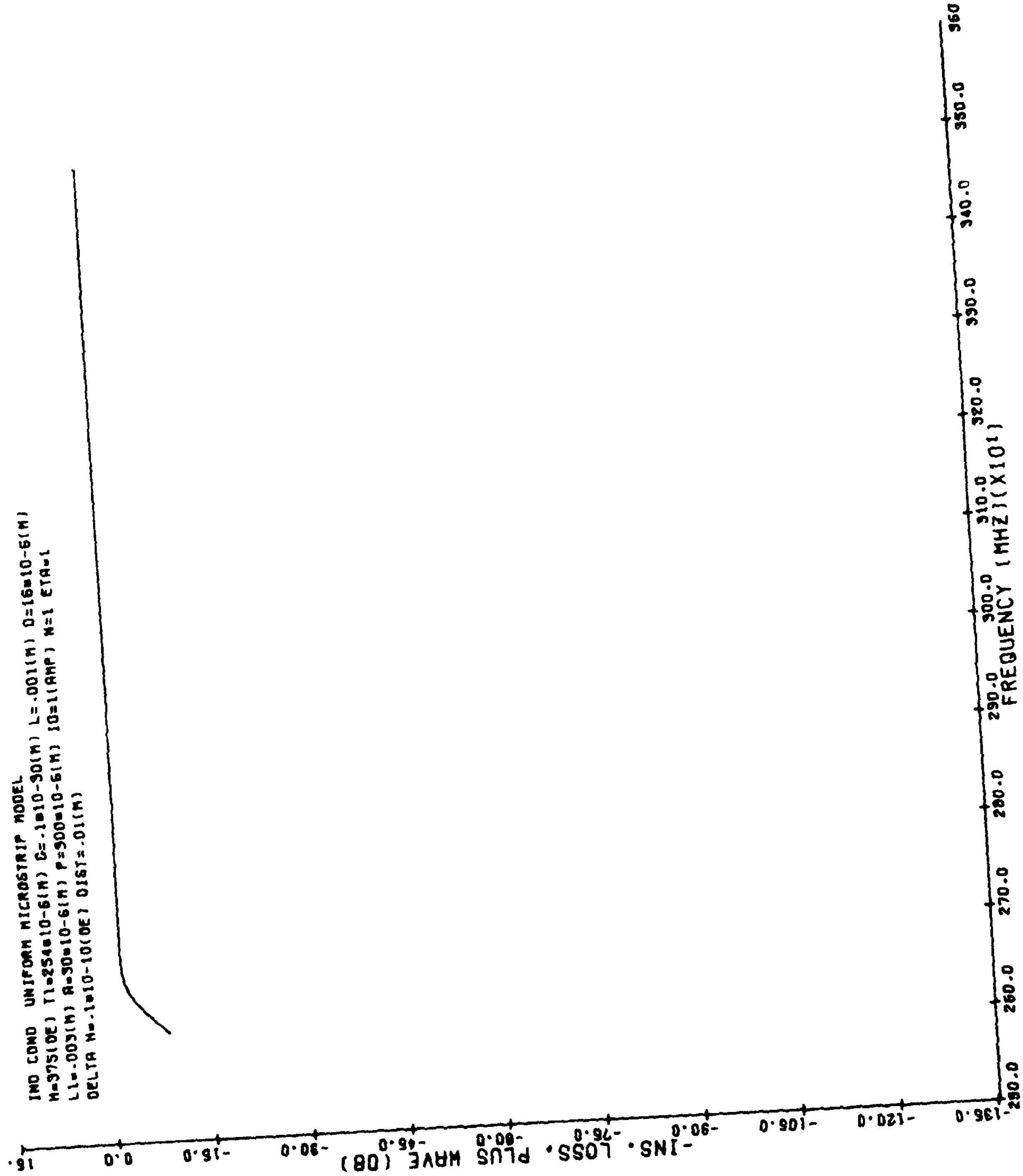

INPUT RESISTANCE (OHMS)
0.0
30.0
60.0
90.0
120.0
150.0
180.0
210.0
240.0
270.0
300
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
FREQUENCY (MHZ)(X10¹)

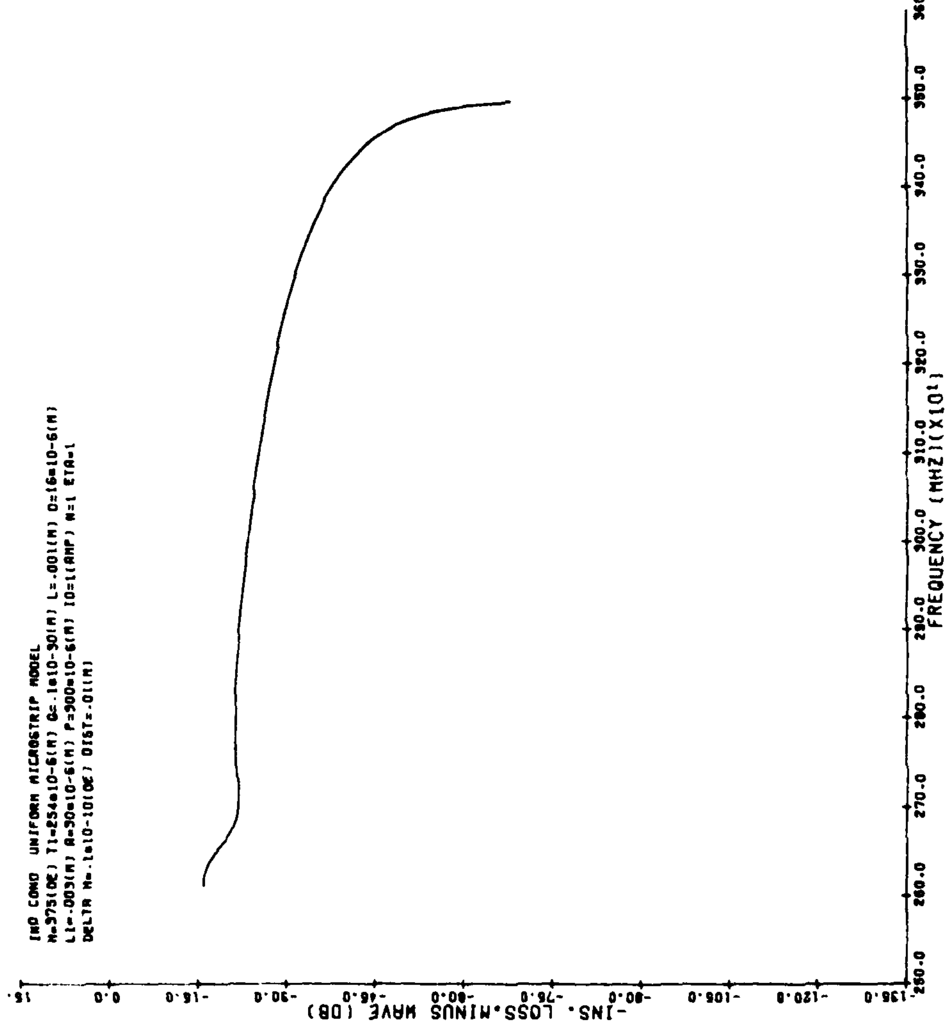
Figure 13


FREQUENCY (MHZ)(X10¹)
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.0
INPUT REACTANCE (OHMS)
-250.0
-200.0
-150.0
-100.0
-50.0
0.0
50.0
100.0
150.0
200.0
250



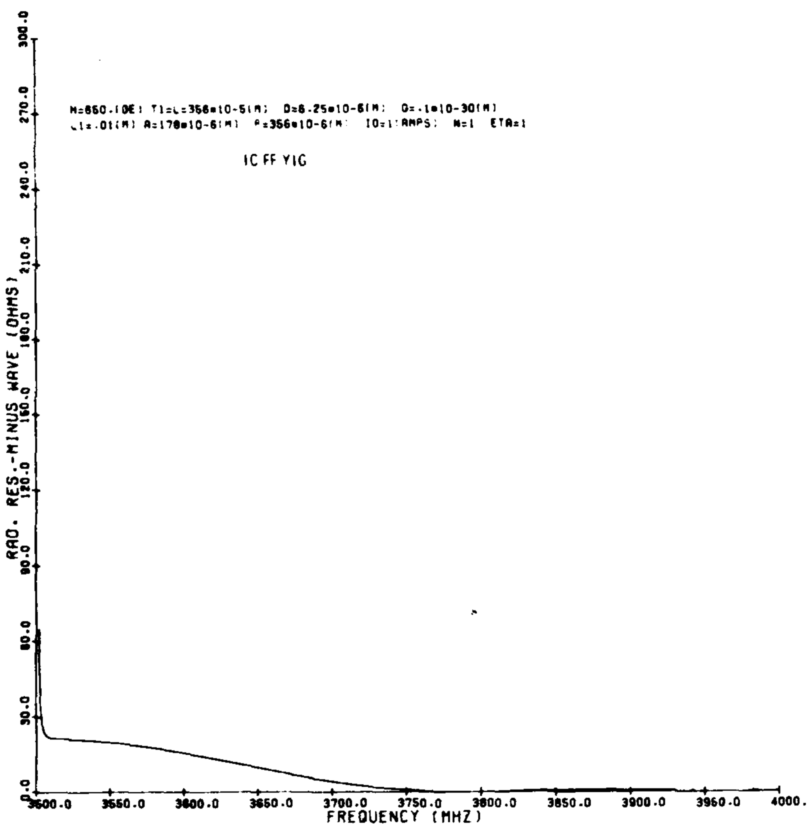
IND COND UNIFORM MICROSTRIP MODEL
M=375(OE) T1=254*10-6(M) G=.1*10-30(M) L=.001(M) D=16*10-6(M)
L1=.003(M) R=30*10-6(M) P=300*10-6(M) IO=1(AMP) N=1 ETA=1
DELTA H=.1*10-10(OE) DIST=.01(M)
15.
0.0
-15.0
-30.0
-45.0
-60.0
-75.0
-90.0
-105.0
-120.0
-135.0
-INS. LOSS, PLUS WAVE (DB)
250.0
260.0
270.0
280.0
290.0
300.0
310.0
320.0
330.0
340.0
350.0
360.
FREQUENCY (MHZ)(X10¹)

Figure 15



IND COND UNIFORM MICROSTRIP MODEL
M=975(OE) T1=254e10-6(M) G=.1e10-90(M) L=.001(M) D=16e10-6(M)
L1=.003(M) A=90e10-6(M) P=900e10-6(M) I0=1(AMP) N=1 ETA=1
DELTA M=.1e10-10(OE) DIST=.01(M)
-INS. LOSS.MINUS WAVE (DB)
FREQUENCY (MHZ)(X10^1)

Figure 16


H=650.(OE) T1=L=356*10-6(M) D=6.25*10-6(M) G=.1*10-30(M)
L1=.01(M) A=178*10-6(M) P=356*10-6(M) IO=1(AMPS) N=1 ETA=1
IC FF YIG
RAD. RES.-MINUS WAVE (OHMS)
FREQUENCY (MHZ)

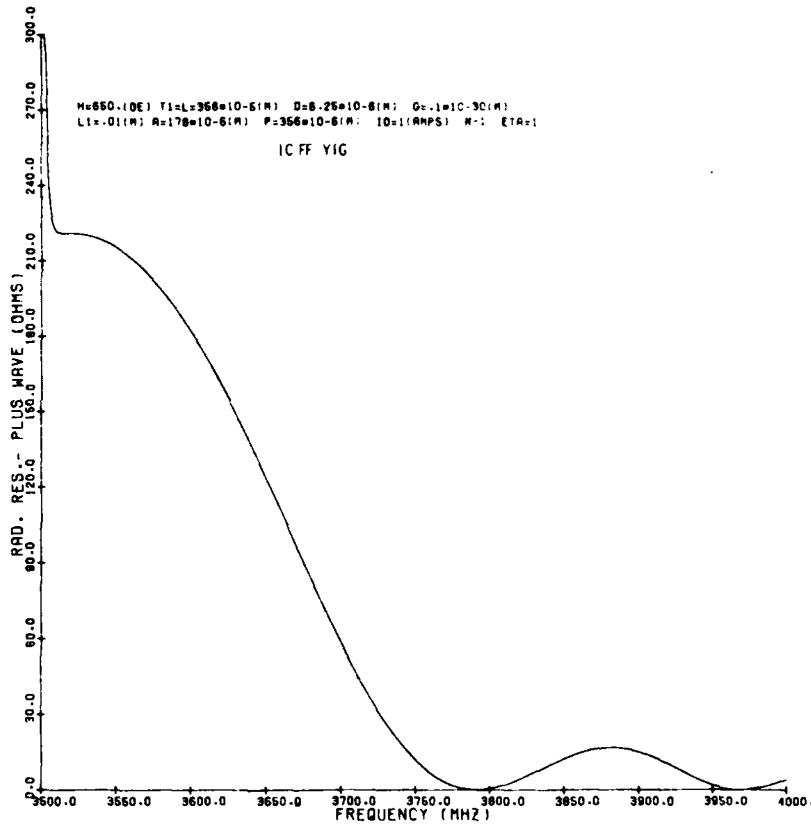

H=650.(OE) T1=L=356*10-6(M) D=6.25*10-6(M) G=.1*10-30(M)
L1=.01(M) A=178*10-6(M) P=356*10-6(M) IO=1(AMPS) N=1 ETA=1
IC FF YIG
RAD. RES.- PLUS WAVE (OHMS)
FREQUENCY (MHZ)

Figure 17

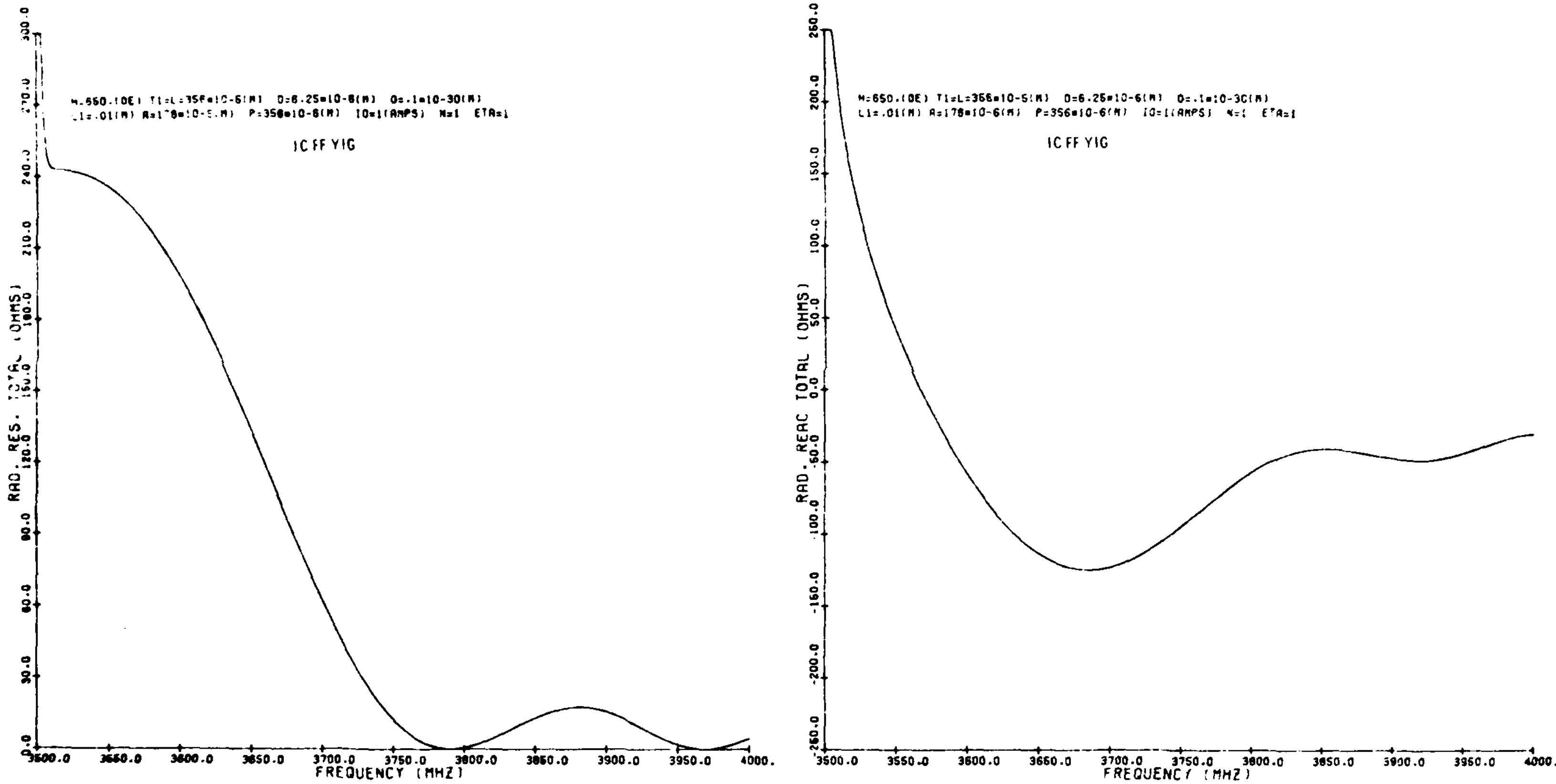

H=650.(OE) T1=L=356*10-6(M) D=6.25*10-6(M) O=.1*10-30(M)
L1=.01(M) A=178*10-6(M) P=356*10-6(M) IO=1(AMPS) N=1 ETA=1
ICFF YIG
RAD. RES. TOTAL (OHMS)
FREQUENCY (MHZ)
RAD. REAC TOTAL (OHMS)
FREQUENCY (MHZ)

Figure 18

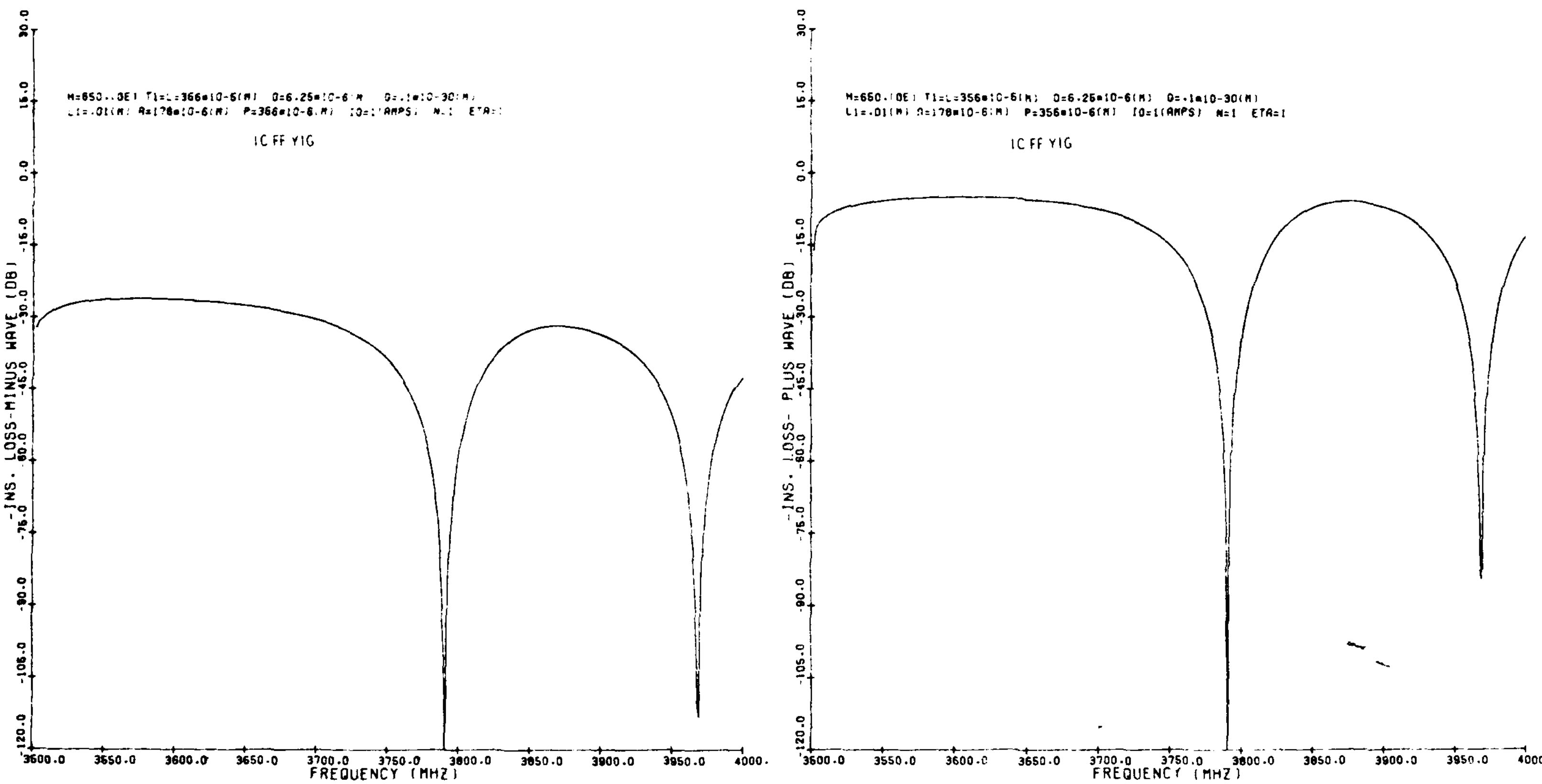

IC FF YIG
-INS. LOSS-MINUS WAVE (DB)
FREQUENCY (MHZ)
IC FF YIG
H=650.(OE) T1=L=356*10-6(M) D=6.25*10-6(M) D=.1*10-30(M)
L1=.01(M) D=178*10-6(M) P=356*10-6(M) IO=1(AMPS) N=1 ETA=1
-INS. LOSS- PLUS WAVE (DB)
FREQUENCY (MHZ)

Figure 19

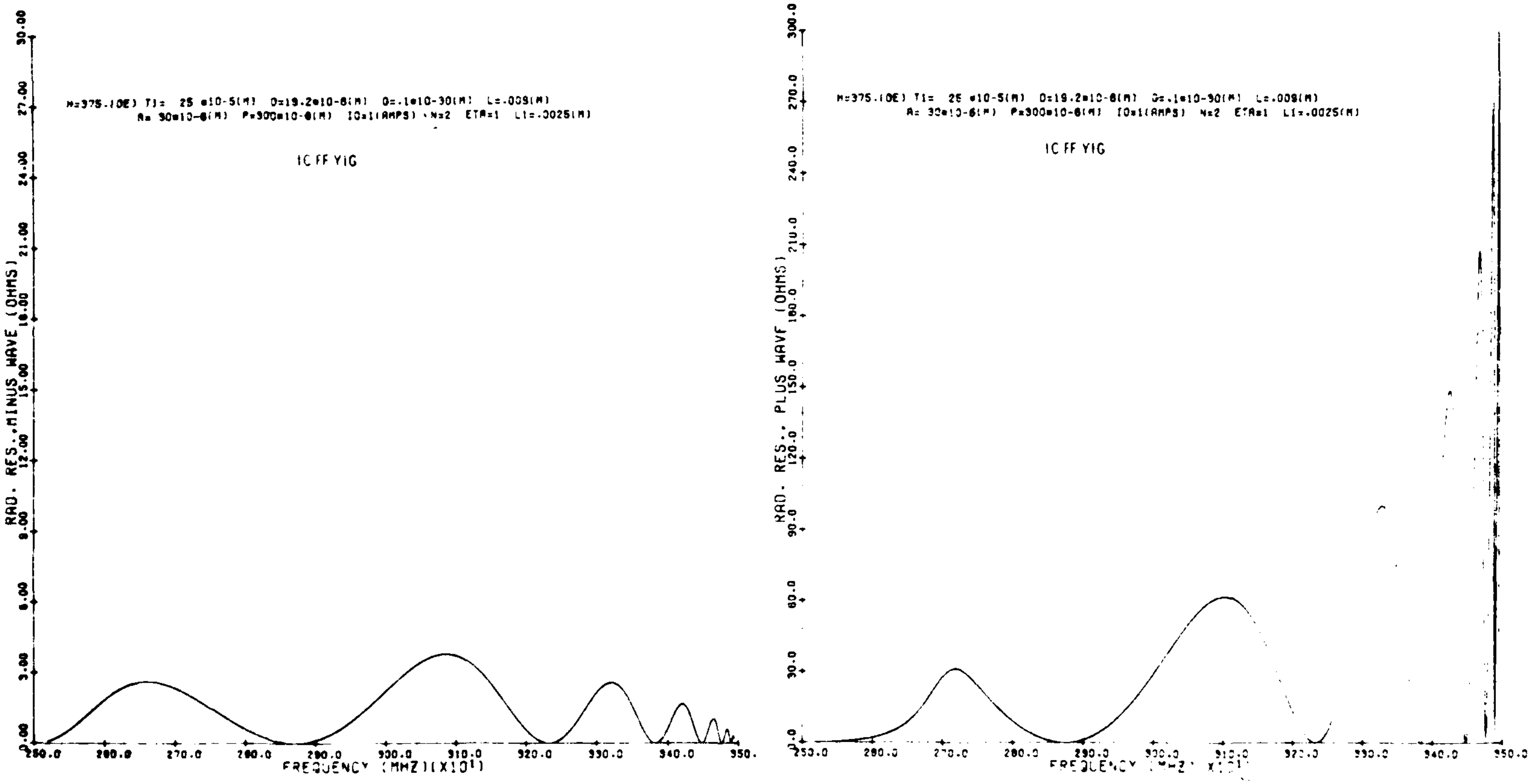

H=375.(OE) TI= 25 *10-5(M) D=19.2*10-6(M) D=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=2 ETA=1 LI=.0025(M)
IC FF YIG
RAD. RES.,MINUS WAVE (OHMS)
FREQUENCY (MHZ)(X10¹)
H=375.(OE) TI= 25 *10-5(M) D=19.2*10-6(M) D=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=2 ETA=1 LI=.0025(M)
IC FF YIG
RAD. RES., PLUS WAVE (OHMS)

Figure 20

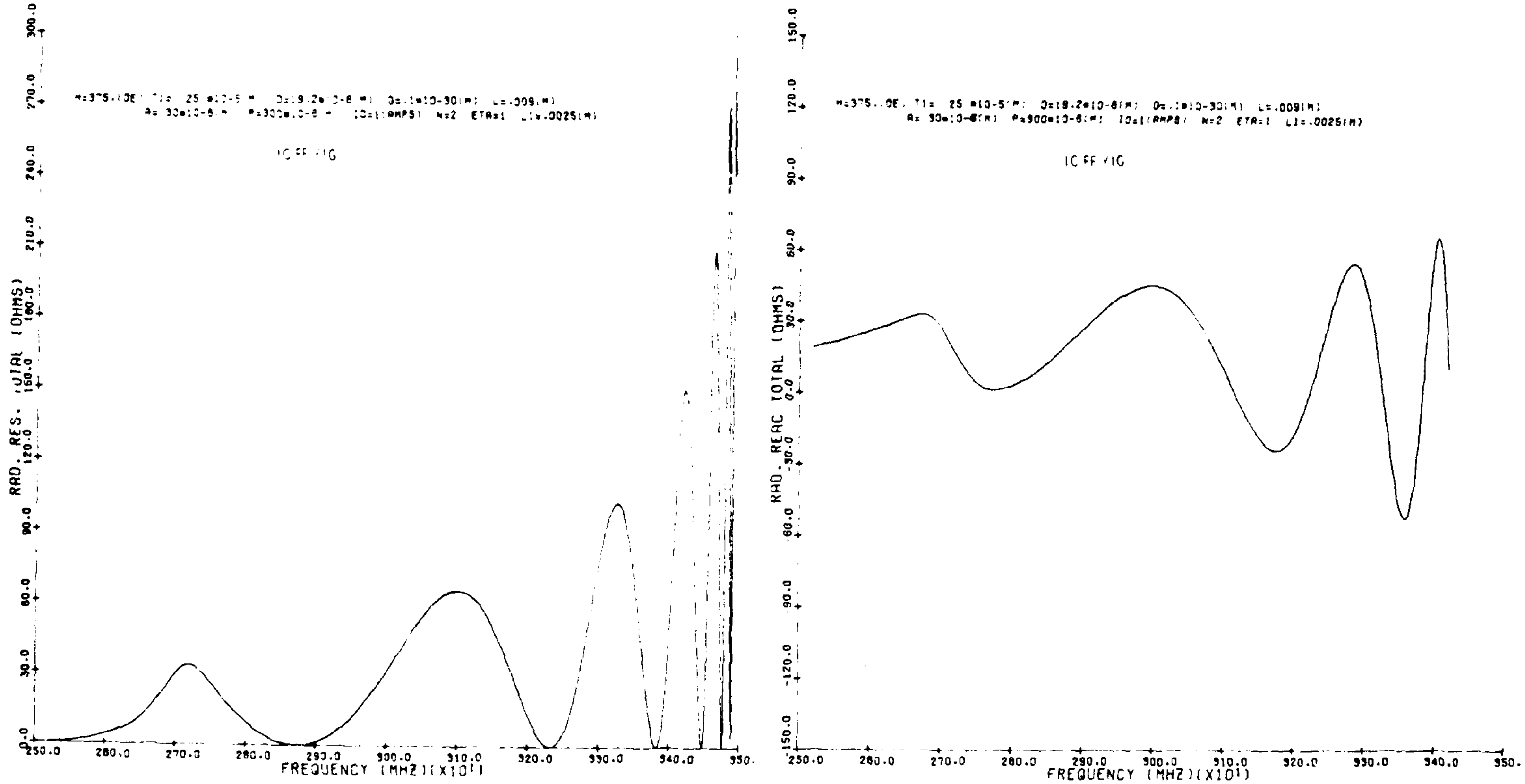
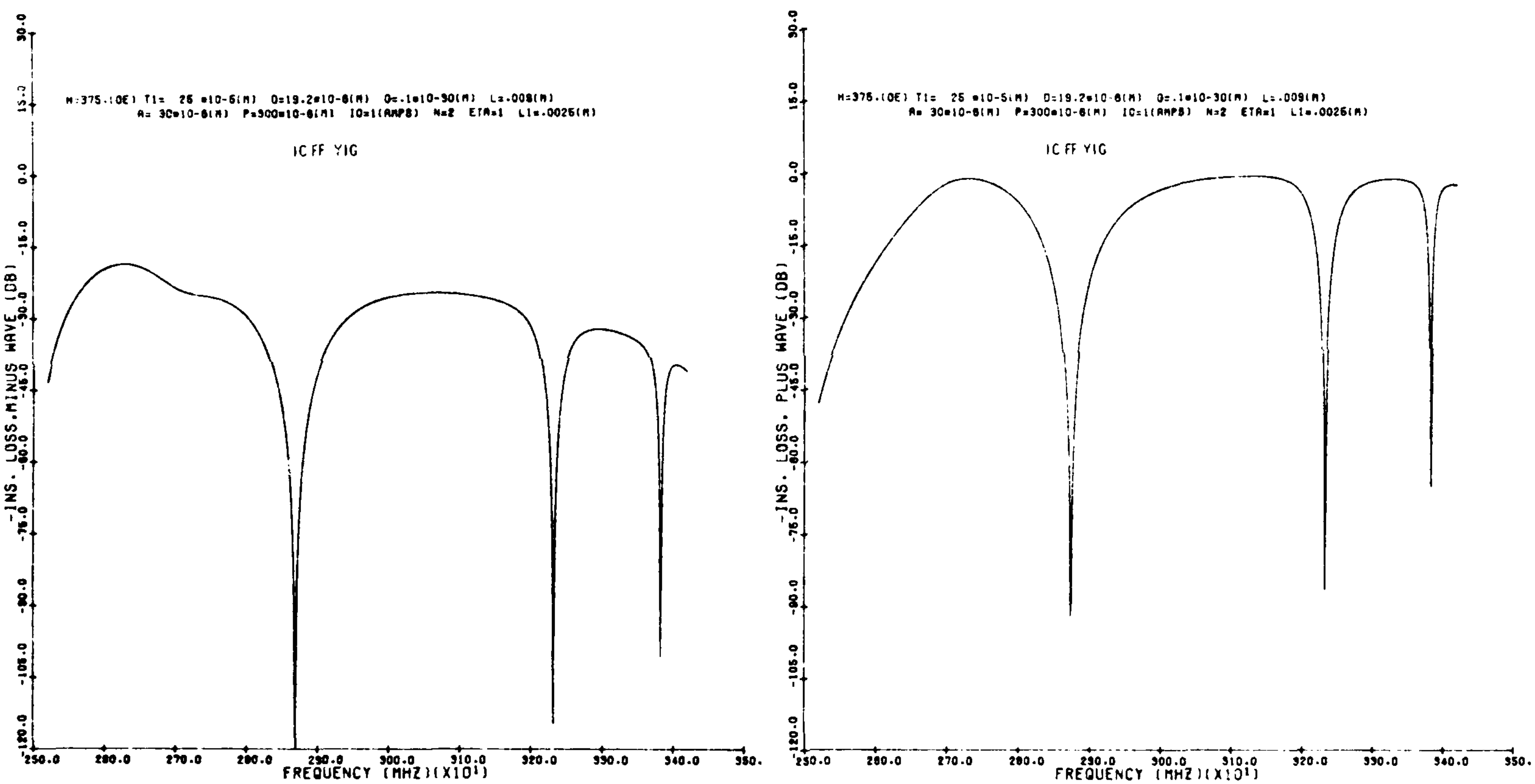

RAD. RES. TOTAL (OHMS)
FREQUENCY (MHZ)(X10¹)
RAD. REAC TOTAL (OHMS)
FREQUENCY (MHZ)(X10¹)

Figure 21



H:375.(OE) T1= 25 *10-5(M) D=19.2*10-6(M) O=.1*10-30(M) L=.008(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=2 ETA=1 L1=.0025(M)
IC FF YIG
-INS. LOSS.MINUS WAVE (DB)
FREQUENCY (MHZ)(X10¹)
H:375.(OE) T1= 25 *10-5(M) D=19.2*10-6(M) O=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=2 ETA=1 L1=.0026(M)
IC FF YIG
-INS. LOSS. PLUS WAVE (DB)
FREQUENCY (MHZ)(X10¹)

Figure 22

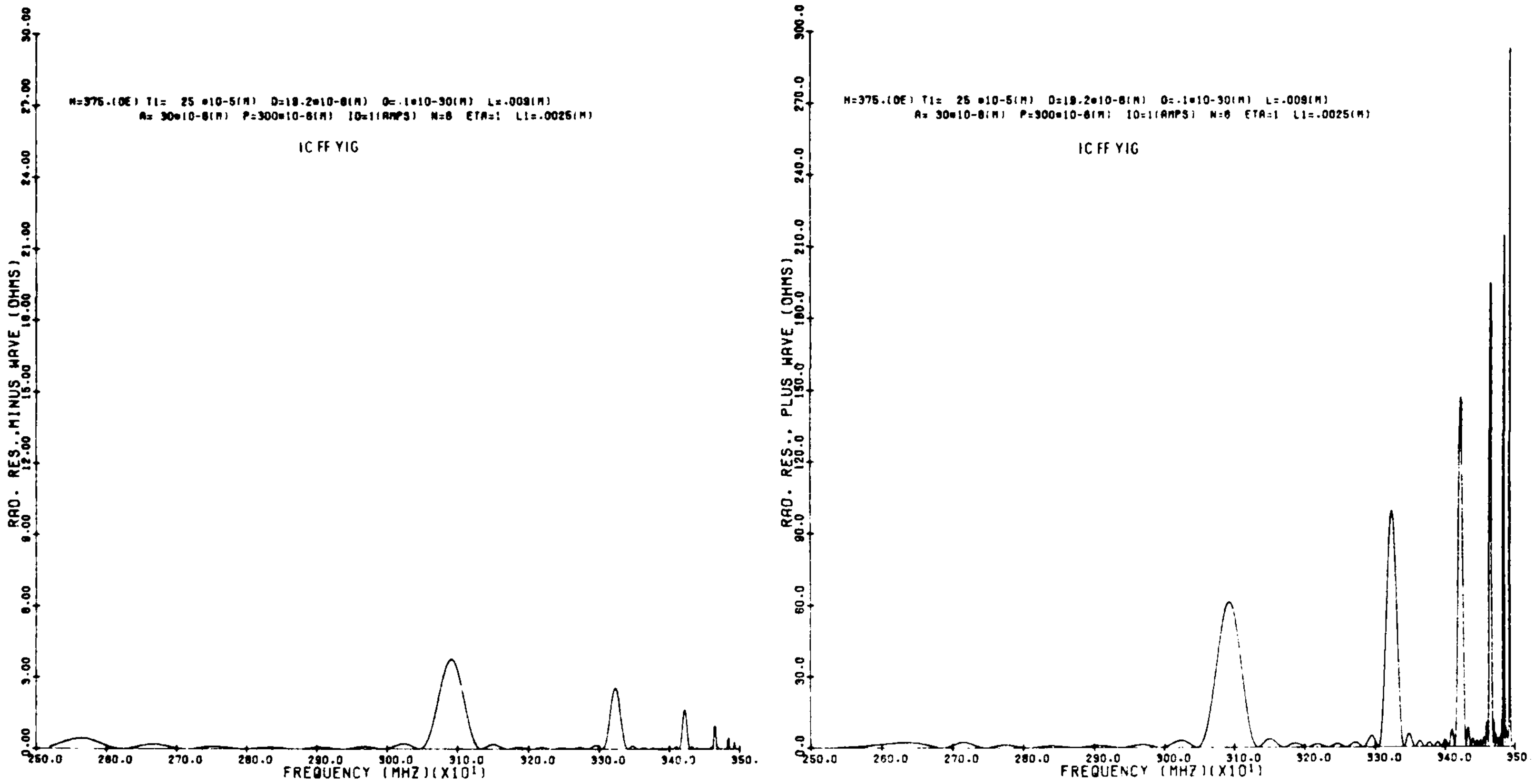
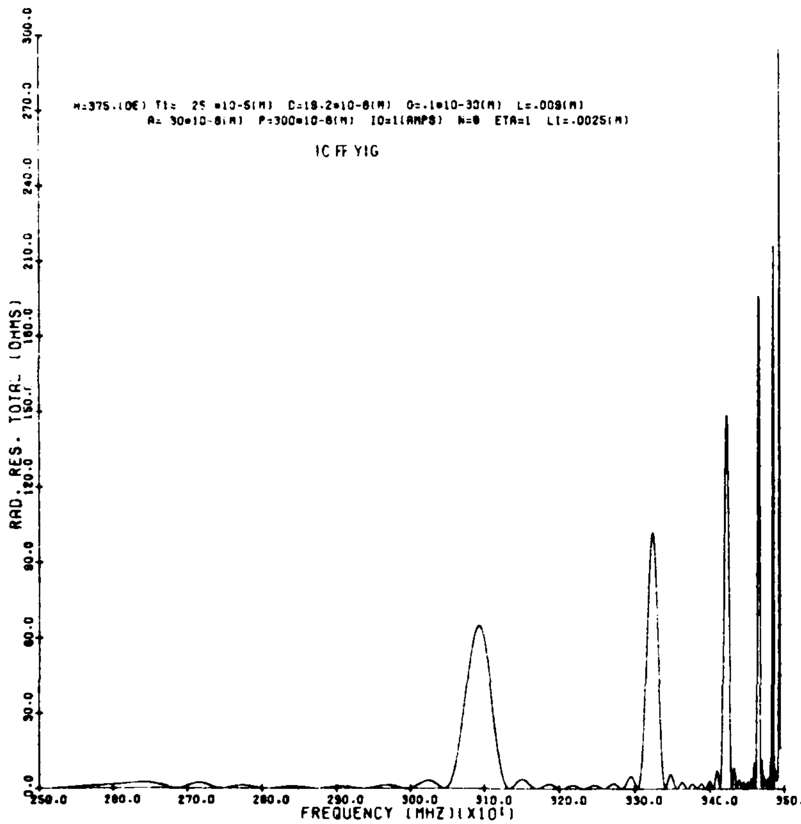
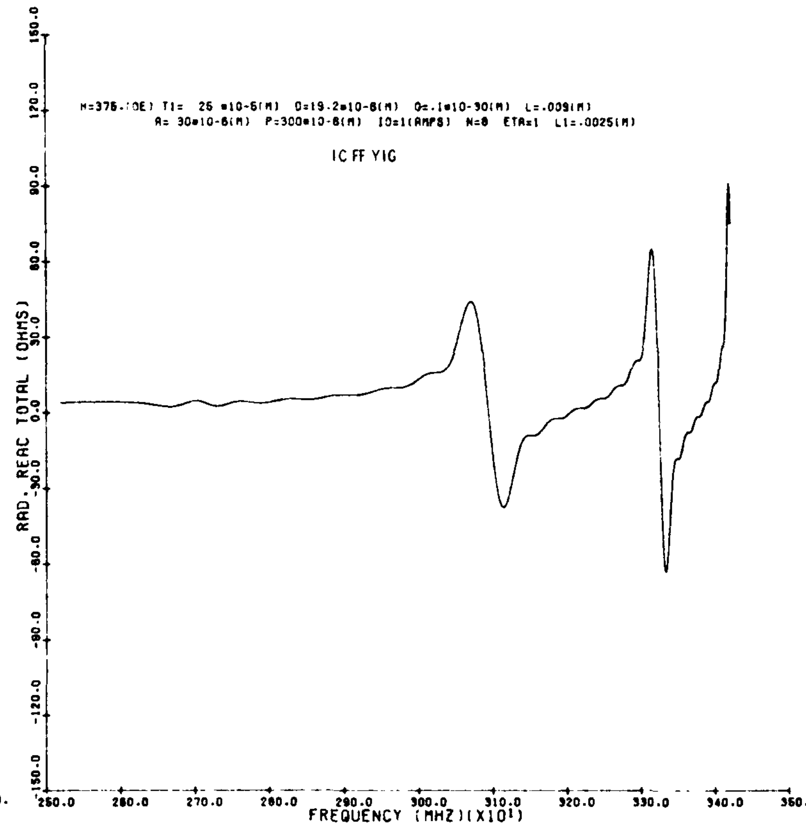

H=375.(OE) T1= 25 *10-5(M) D=19.2*10-8(M) O=.1*10-30(M) L=.009(M)
A= 30*10-8(M) P=300*10-8(M) IO=1(AMPS) N=8 ETA=1 L1=.0025(M)
IC FF YIG
RAD. RES.,MINUS WAVE (OHMS)
FREQUENCY (MHZ)(X10¹)
H=375.(OE) T1= 25 *10-5(M) D=19.2*10-8(M) O=.1*10-30(M) L=.009(M)
A= 30*10-8(M) P=300*10-8(M) IO=1(AMPS) N=8 ETA=1 L1=.0025(M)
IC FF YIG
RAD. RES., PLUS WAVE (OHMS)
FREQUENCY (MHZ)(X10¹)

Figure 23



H=375.(OE) TI= 25 *10-5(M) D=19.2*10-6(M) O=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=8 ETA=1 L1=.0025(M)
IC FF YIG
RAD. RES. TOTAL (OHMS)
FREQUENCY (MHZ)(X10[1])



H=375.(OE) TI= 25 *10-5(M) D=19.2*10-6(M) O=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=8 ETA=1 L1=.0025(M)
IC FF YIG
RAD. REAC TOTAL (OHMS)
FREQUENCY (MHZ)(X10[1])

Figure 24

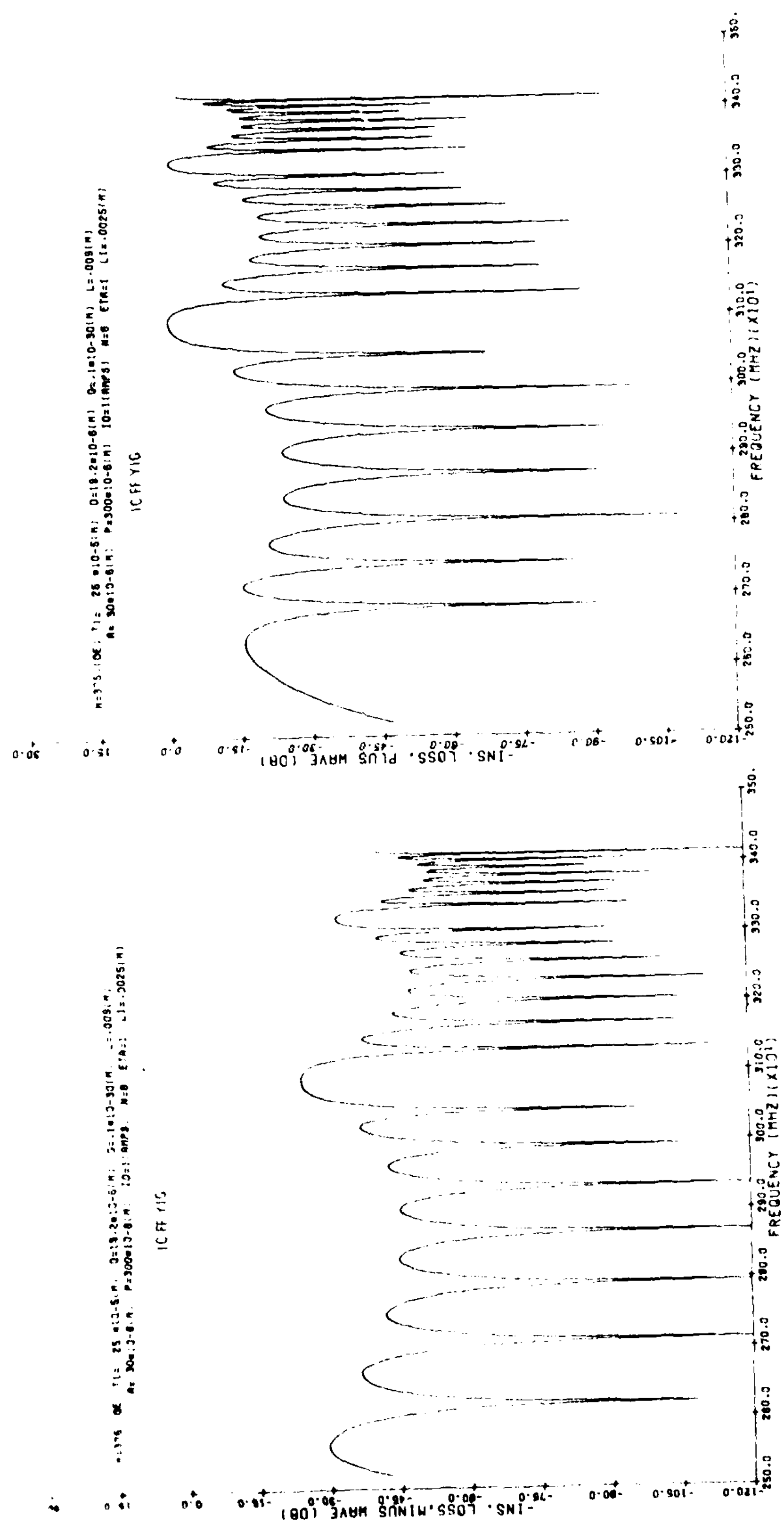
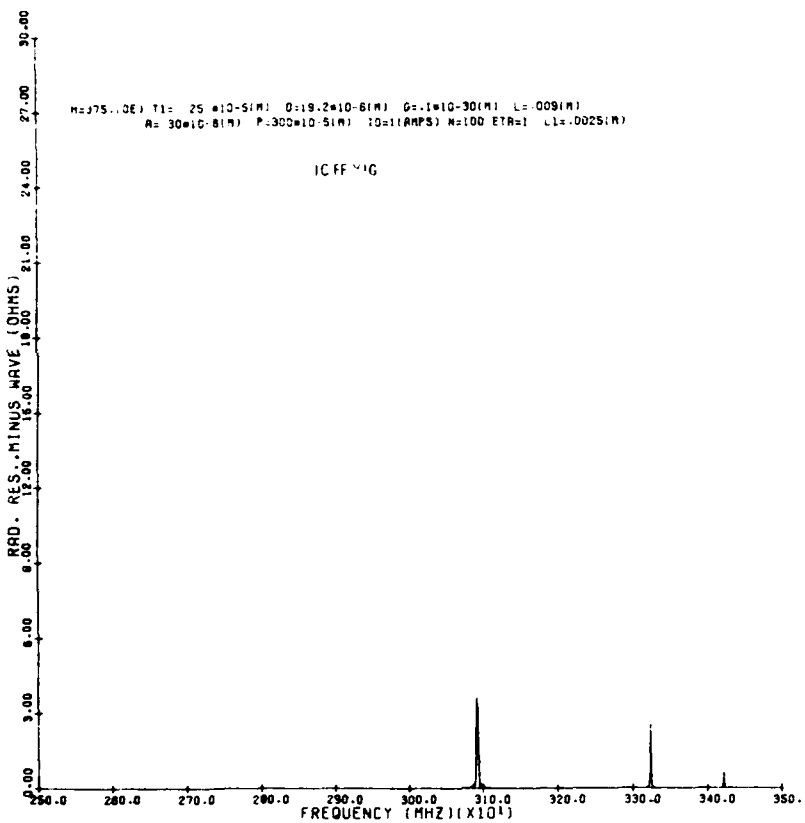

ICFF YIG
-INS. LOSS, PLUS WAVE (DB)
FREQUENCY (MHZ)(X10[1])
ICFF YIG
-INS. LOSS,MINUS WAVE (DB)
FREQUENCY (MHZ)(X10[1])

Figure 25


H=375..0E) T1= 25 *10-5(M) D=19.2*10-6(M) G=.1*10-30(M) L=.009(M)
A= 30*10-8(M) P=300*10-5(M) I0=1(AMPS) N=100 ETA=1 L1=.0025(M)
IC FF YIG
RAD. RES..MINUS WAVE (OHMS)
FREQUENCY (MHZ)(X10¹)

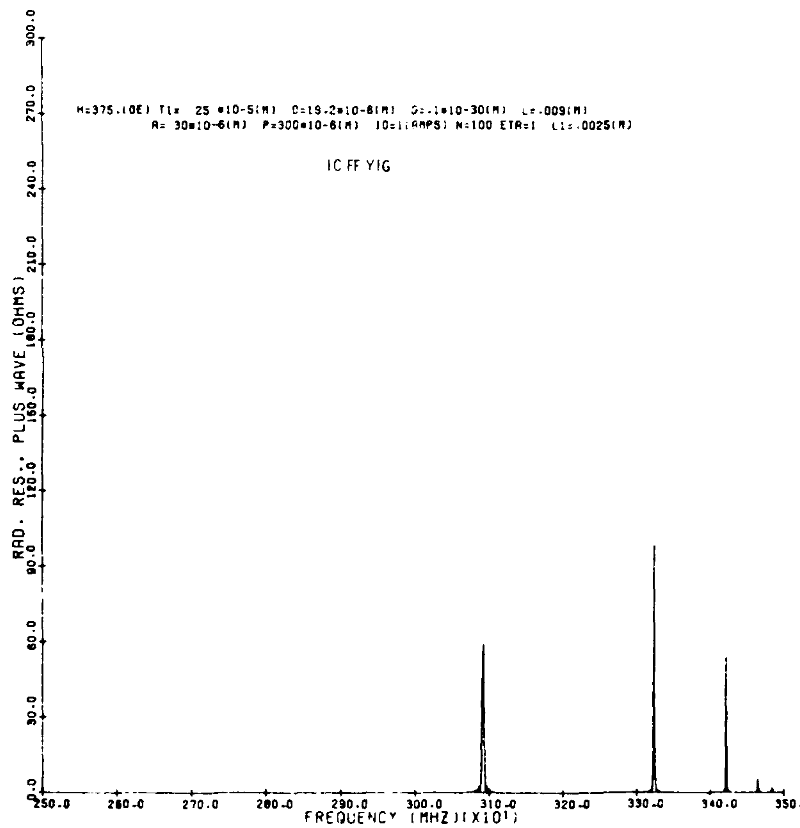

H=375.(0E) T1= 25 *10-5(M) D=19.2*10-6(M) G=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) I0=1(AMPS) N=100 ETA=1 L1=.0025(M)
IC FF YIG
RAD. RES., PLUS WAVE (OHMS)
FREQUENCY (MHZ)(X10¹)

Figure 26

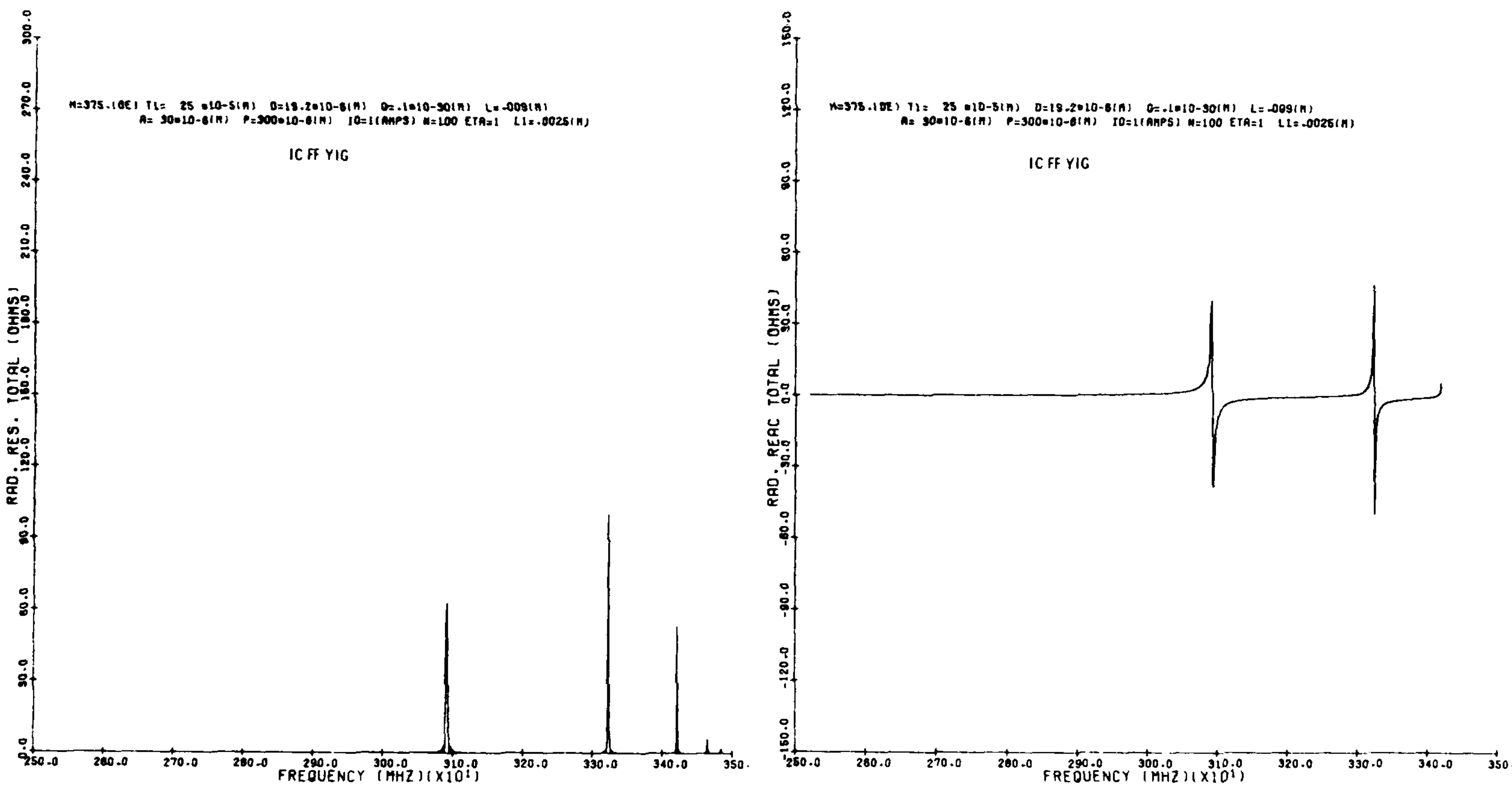
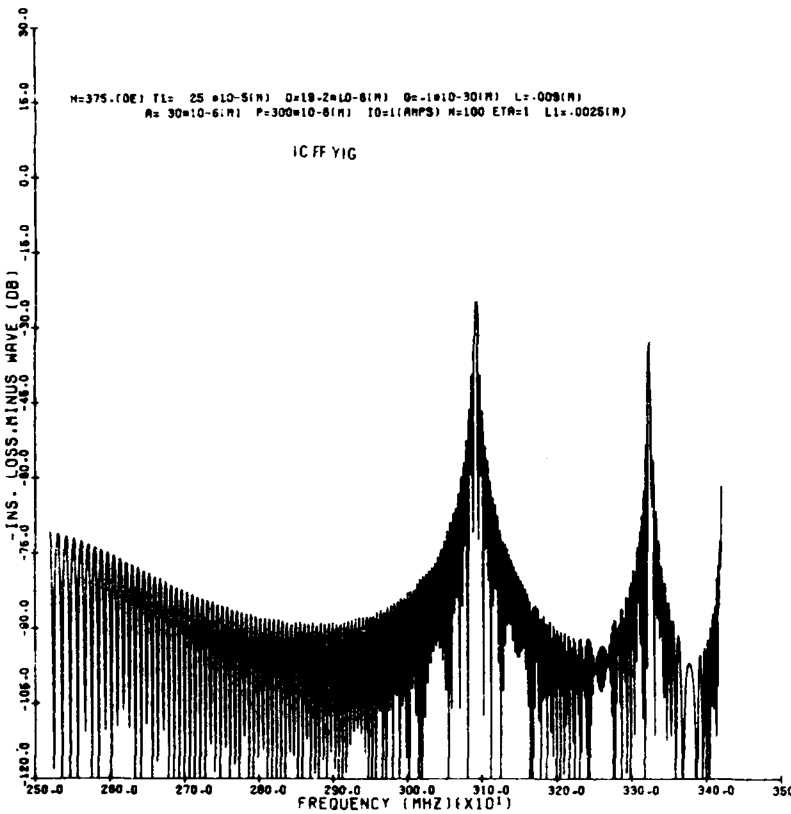

H=375.(OE) T1= 25 *10-5(M) D=19.2*10-6(M) O=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=100 ETA=1 L1=.0025(M)
IC FF YIG
RAD. RES. TOTAL (OHMS)
FREQUENCY (MHZ)(X10¹)
RAD. REAC TOTAL (OHMS)
FREQUENCY (MHZ)(X10¹)

Figure 27


H=375.(OE) T1= 25 *10-5(M) D=19.2*10-6(M) G=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=100 ETA=1 L1=.0025(M)
IC FF YIG
-INS. LOSS.MINUS WAVE (DB)
FREQUENCY (MHZ)(X10^1)

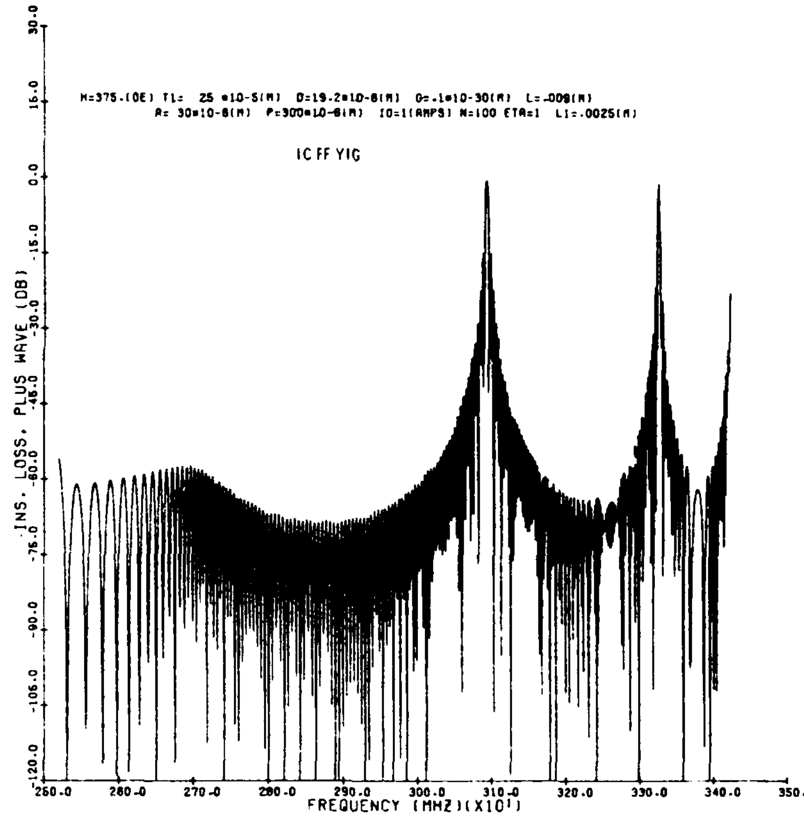

H=375.(OE) T1= 25 *10-5(M) D=19.2*10-6(M) G=.1*10-30(M) L=.009(M)
A= 30*10-6(M) P=300*10-6(M) IO=1(AMPS) N=100 ETA=1 L1=.0025(M)
IC FF YIG
-INS. LOSS. PLUS WAVE (DB)
FREQUENCY (MHZ)(X10^1)

Figure 28

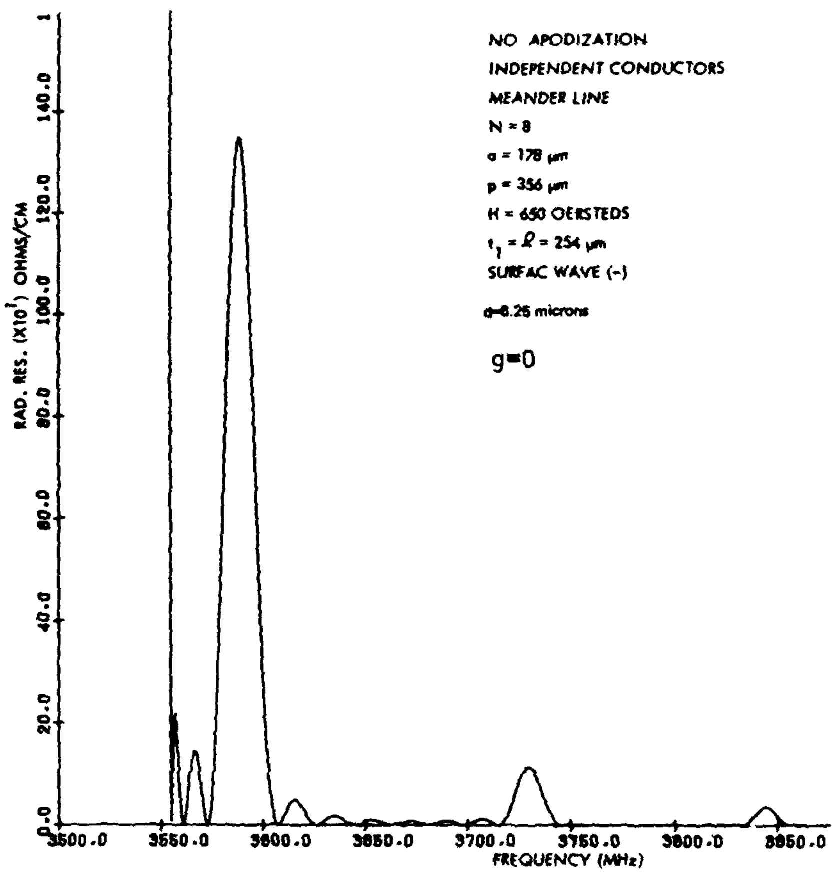

NO APODIZATION
INDEPENDENT CONDUCTORS
MEANDER LINE
N = 8
a = 178 μm
p = 356 μm
H = 650 OERSTEDS
t1 = ℓ = 254 μm
SURFAC WAVE (-)
d=6.25 microns
g=0
RAD. RES. (X10^1) OHMS/CM
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
3500.0
3550.0
3600.0
3650.0
3700.0
3750.0
3800.0
3850.0
FREQUENCY (MHz)

Figure 29

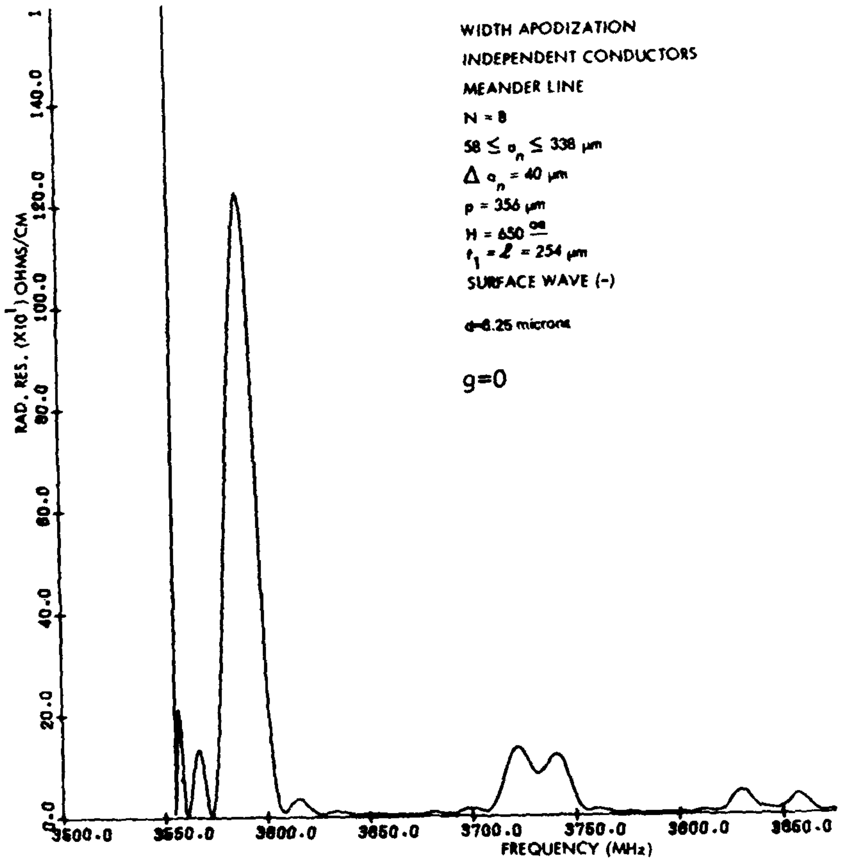
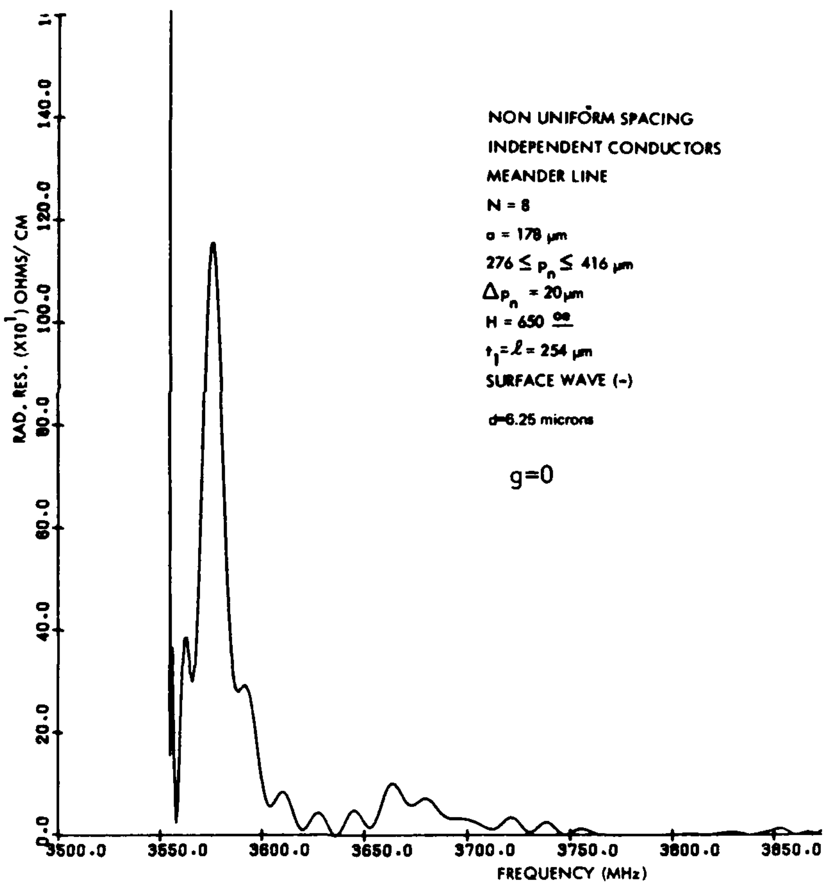

RAD. RES. (X10^1) OHMS/CM
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
3500.0
3550.0
3600.0
3650.0
3700.0
3750.0
3800.0
3850.0
FREQUENCY (MHz)
WIDTH APODIZATION
INDEPENDENT CONDUCTORS
MEANDER LINE
N = 8
$58 \leq a_n \leq 338$ μm
$\Delta a_n = 40$ μm
p = 356 μm
H = 650 oe
$r_1 = \ell = 254$ μm
SURFACE WAVE (-)
d=6.25 microns
g=0

Figure 30



NON UNIFORM SPACING
INDEPENDENT CONDUCTORS
MEANDER LINE
N = 8
a = 178 μm
276 ≤ p_n ≤ 416 μm
Δp_n = 20μm
H = 650 oe
$t_1 = \ell$ = 254 μm
SURFACE WAVE (-)
d=6.25 microns
g=0
RAD. RES. (X10^1) OHMS/ CM
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
3500.0
3550.0
3600.0
3650.0
3700.0
3750.0
3800.0
3850.0
FREQUENCY (MHz)

Figure 31

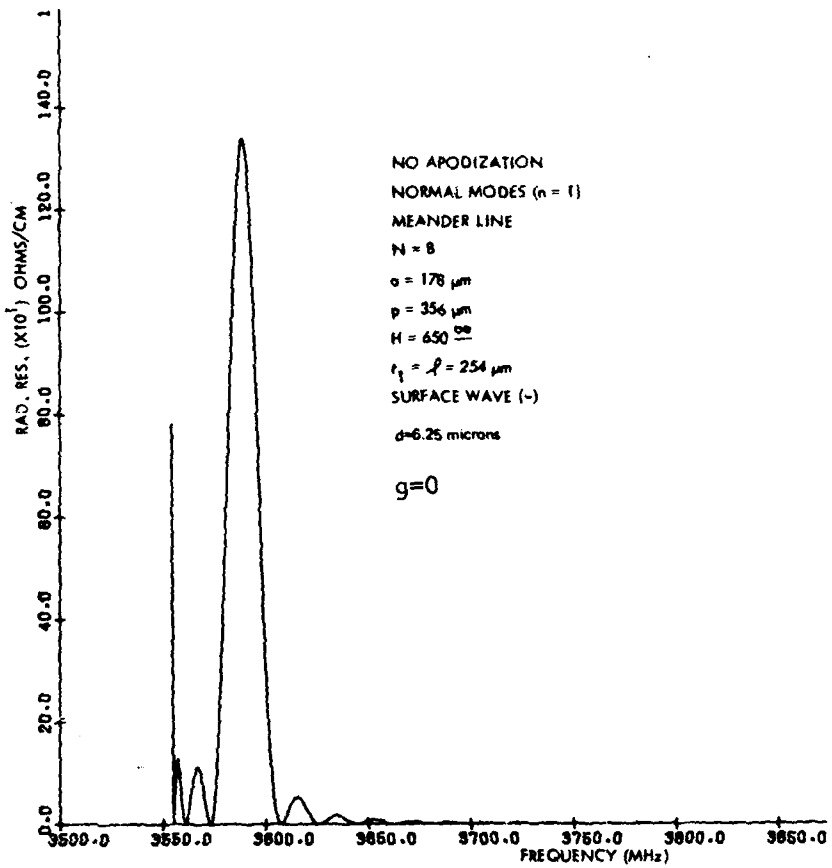

NO APODIZATION
NORMAL MODES (n = 1)
MEANDER LINE
N = 8
a = 178 μm
p = 356 μm
H = 650 Oe
r_1 = ℓ = 254 μm
SURFACE WAVE (-)
d=6.25 microns
g=0
RAD. RES. (X10^1) OHMS/CM
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
3500.0
3550.0
3600.0
3650.0
3700.0
3750.0
3800.0
3850.0
FREQUENCY (MHz)

Figure 32

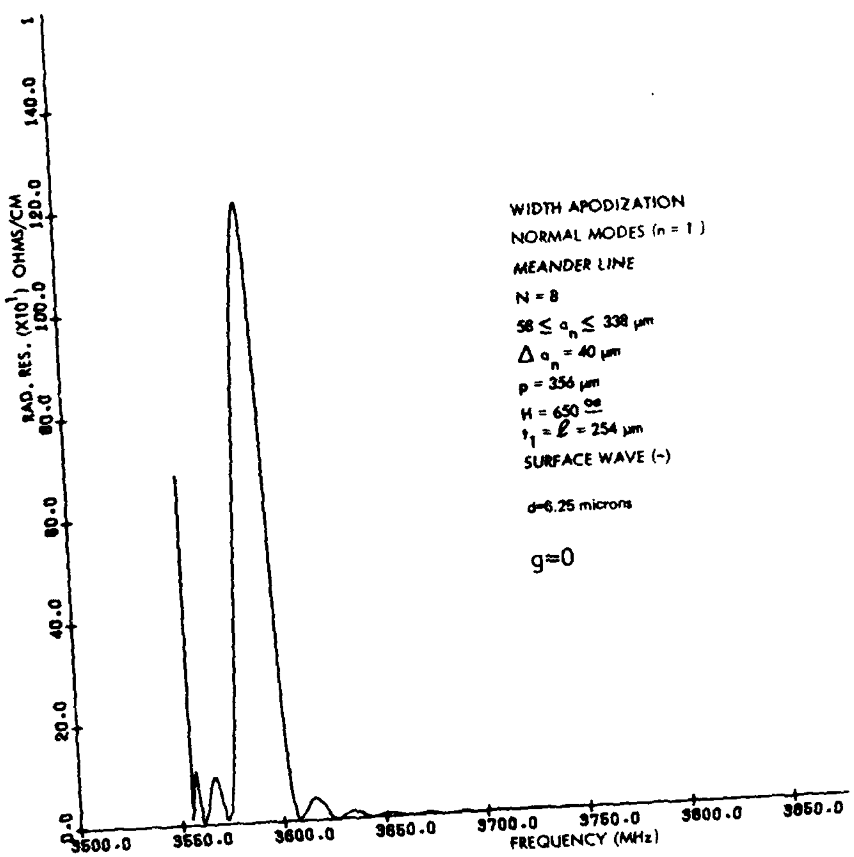

WIDTH APODIZATION
NORMAL MODES (n = 1)
MEANDER LINE
N = 8
58 ≤ a_n ≤ 338 μm
Δ a_n = 40 μm
p = 356 μm
H = 650 Oe
t_1 = ℓ = 254 μm
SURFACE WAVE (-)
d=6.25 microns
g=0
RAD. RES. (X10¹) OHMS/CM
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
3500.0
3550.0
3600.0
3650.0
3700.0
3750.0
3800.0
3850.0
FREQUENCY (MHz)

Figure 33

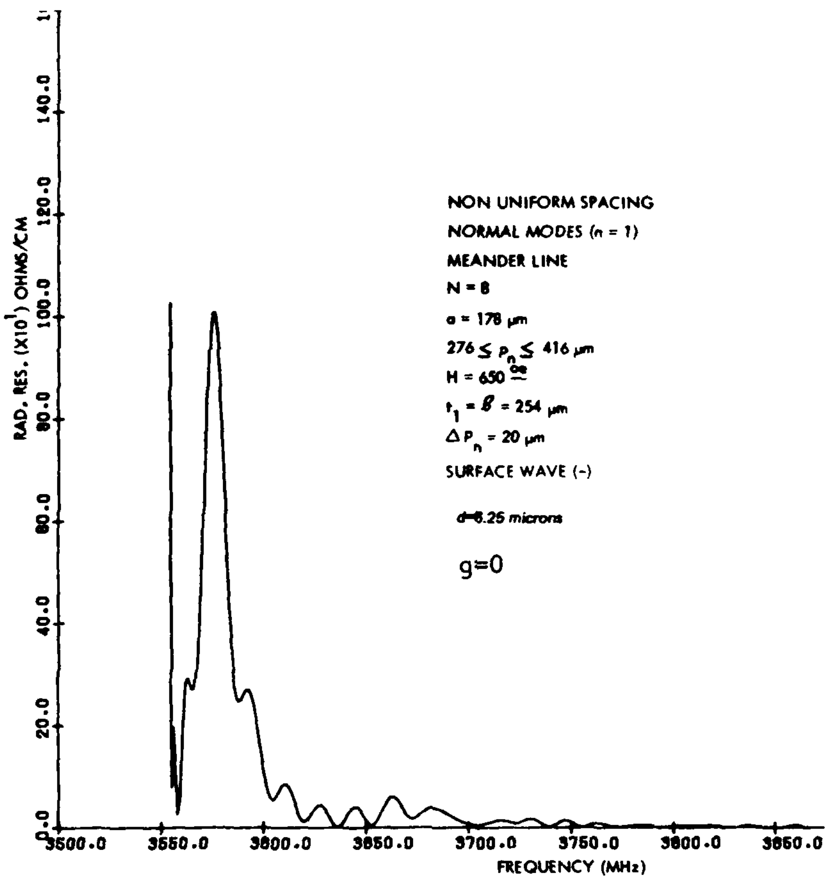

NON UNIFORM SPACING
NORMAL MODES (n = 1)
MEANDER LINE
N = 8
a = 178 μm
276 ≤ P_n ≤ 416 μm
H = 650 Oe
t_1 = ℓ = 254 μm
ΔP_n = 20 μm
SURFACE WAVE (-)
d=6.25 microns
g=0
RAD. RES. (X10^1) OHMS/CM
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
3500.0
3550.0
3600.0
3650.0
3700.0
3750.0
3800.0
3850.0
FREQUENCY (MHz)

Figure 34

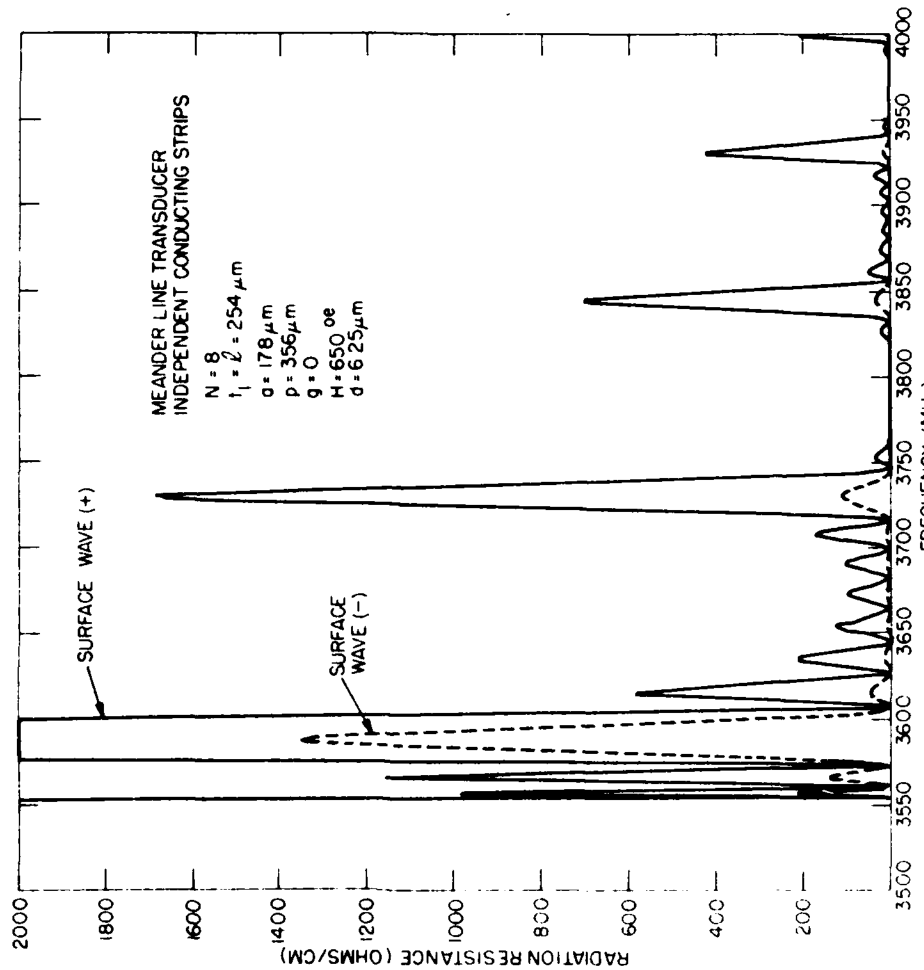

MEANDER LINE TRANSDUCER
INDEPENDENT CONDUCTING STRIPS
N = 8
$t_1 = \ell = 254\,\mu m$
$a = 178\,\mu m$
$p = 356\,\mu m$
g = 0
H = 650 oe
$d = 6.25\,\mu m$
SURFACE WAVE (+)
SURFACE WAVE (−)
RADIATION RESISTANCE (OHMS/CM)
FREQUENCY (MHz)
2000
1800
1600
1400
1200
1000
800
600
400
200
3500
3550
3600
3650
3700
3750
3800
3850
3900
3950
4000

Figure 35

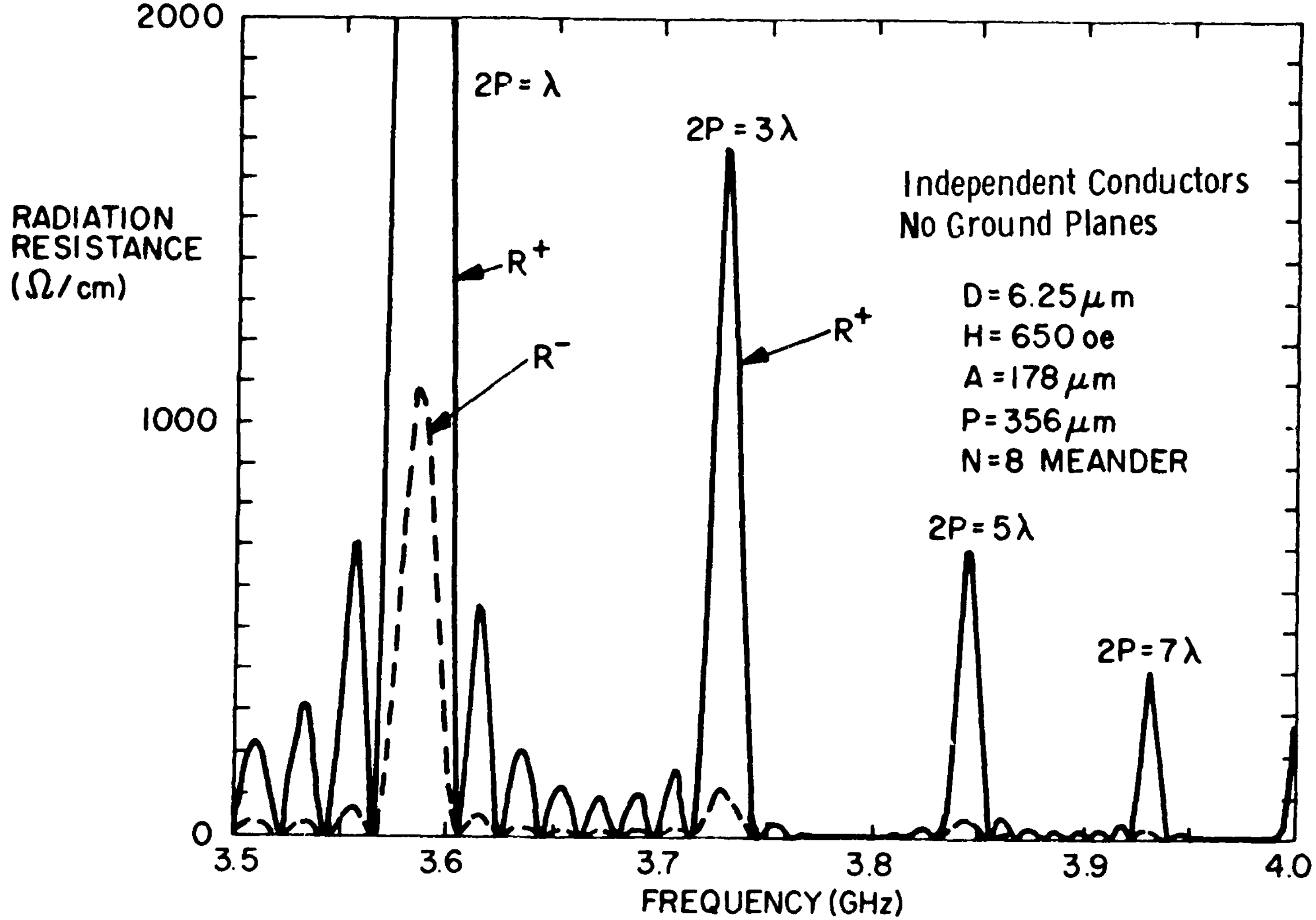

2000
1000
0
RADIATION RESISTANCE (Ω/cm)
3.5
3.6
3.7
3.8
3.9
4.0
FREQUENCY (GHz)
2P = λ
R+
R−
2P = 3λ
R+
2P = 5λ
2P = 7λ
Independent Conductors
No Ground Planes
D = 6.25 μm
H = 650 oe
A = 178 μm
P = 356 μm
N = 8 MEANDER

Figure 36

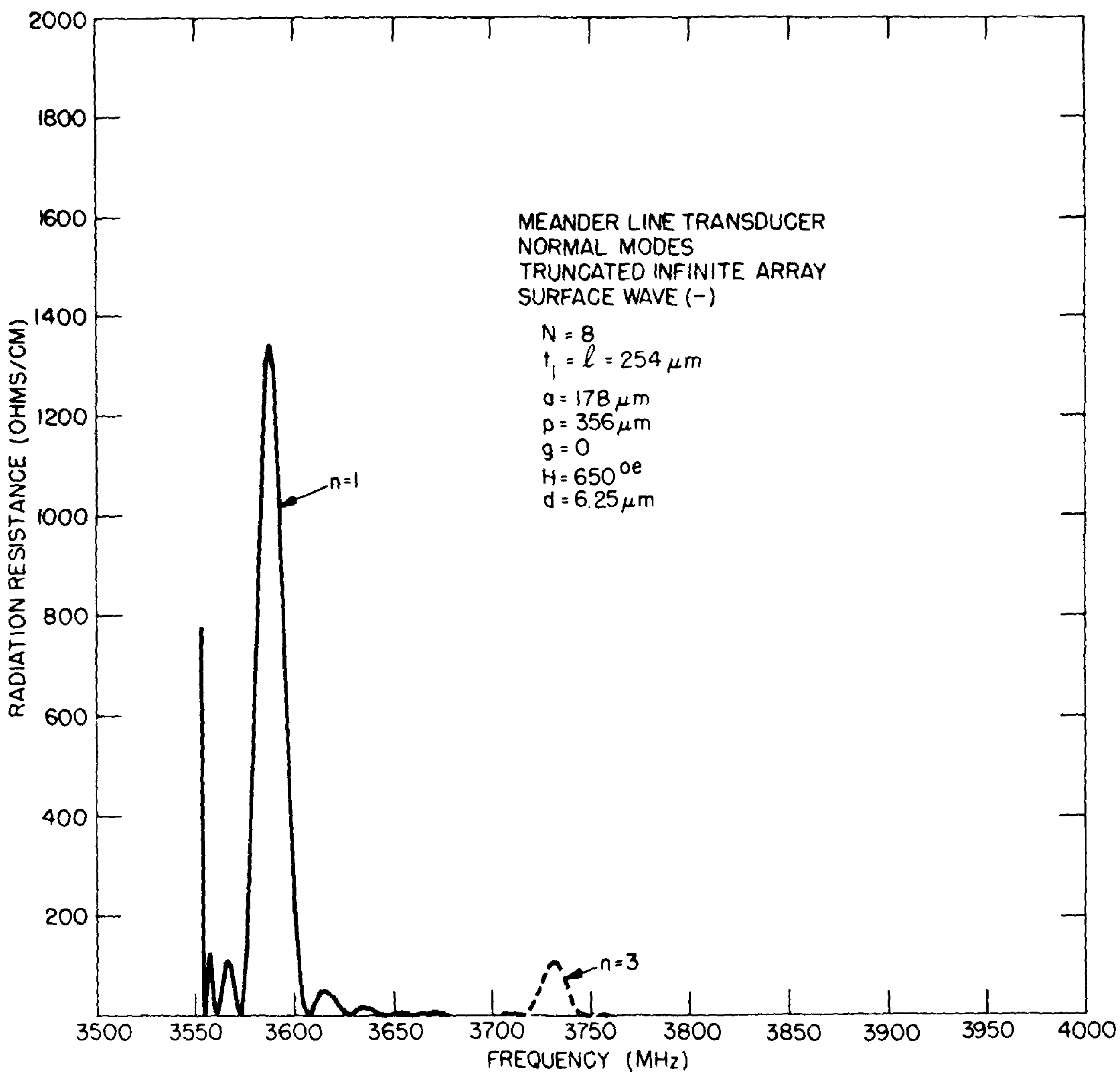

MEANDER LINE TRANSDUCER
NORMAL MODES
TRUNCATED INFINITE ARRAY
SURFACE WAVE (−)
N = 8
$t_1 = \ell = 254\ \mu m$
$a = 178\ \mu m$
$p = 356\ \mu m$
$g = 0$
$H = 650^{oe}$
$d = 6.25\ \mu m$
n=1
n=3
FREQUENCY (MHz)
RADIATION RESISTANCE (OHMS/CM)
3500
3550
3600
3650
3700
3750
3800
3850
3900
3950
4000
2000
1800
1600
1400
1200
1000
800
600
400
200

Figure 37

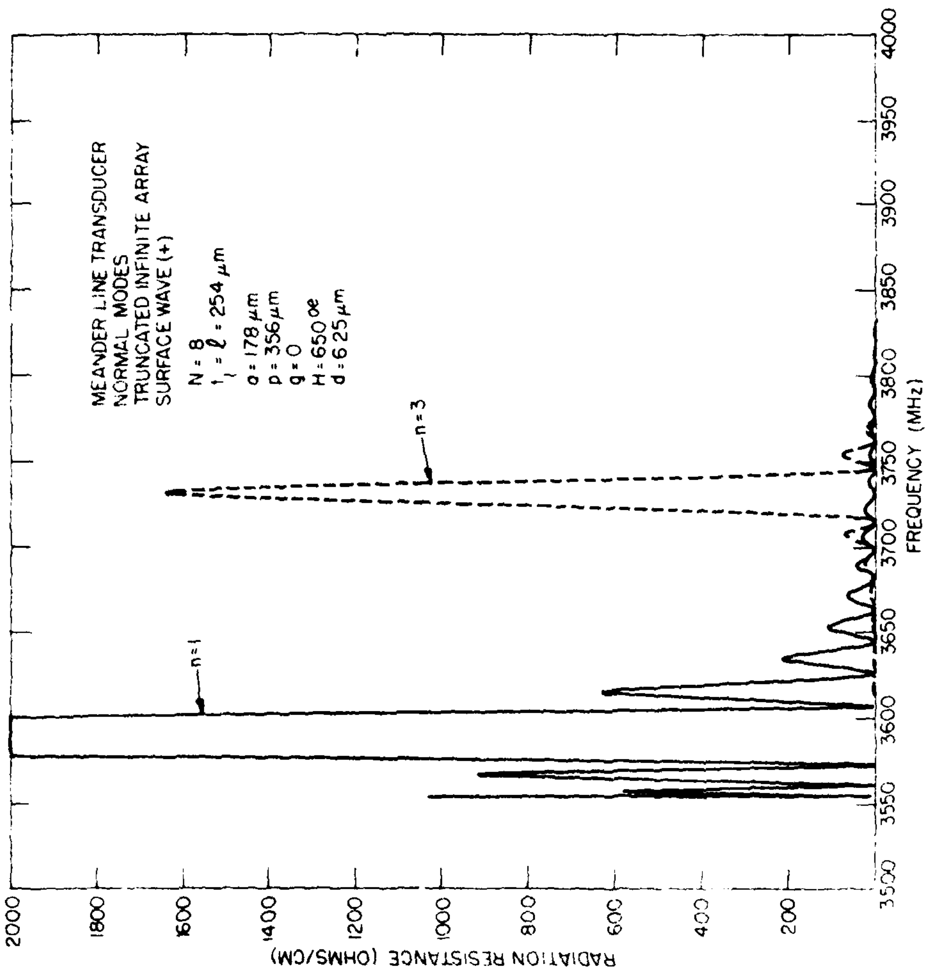

MEANDER LINE TRANSDUCER
NORMAL MODES
TRUNCATED INFINITE ARRAY
SURFACE WAVE (+)
N = 8
$l_1 = l = 254\ \mu m$
$a = 178\ \mu m$
$p = 356\ \mu m$
$g = 0$
$H = 650$ oe
$d = 625\ \mu m$
n=1
n=3
RADIATION RESISTANCE (OHMS/CM)
2000
1800
1600
1400
1200
1000
800
600
400
200
FREQUENCY (MHz)
3500
3550
3600
3650
3700
3750
3800
3850
3900
3950
4000

Figure 38

AD-A102 207 LOWELL UNIV MA F/G 20/3
ANALYSIS AND COMPUTER STUDIES FOR MAGNETOSTATIC SURFACE WAVE TR--ETC(U)
MAY 81 J I WEINBERG F19628-80-C-0029
UNCLASSIFIED RADC-TR-81-96 NL

2 of 2

END
DATE
FILMED
8 81
DTIC

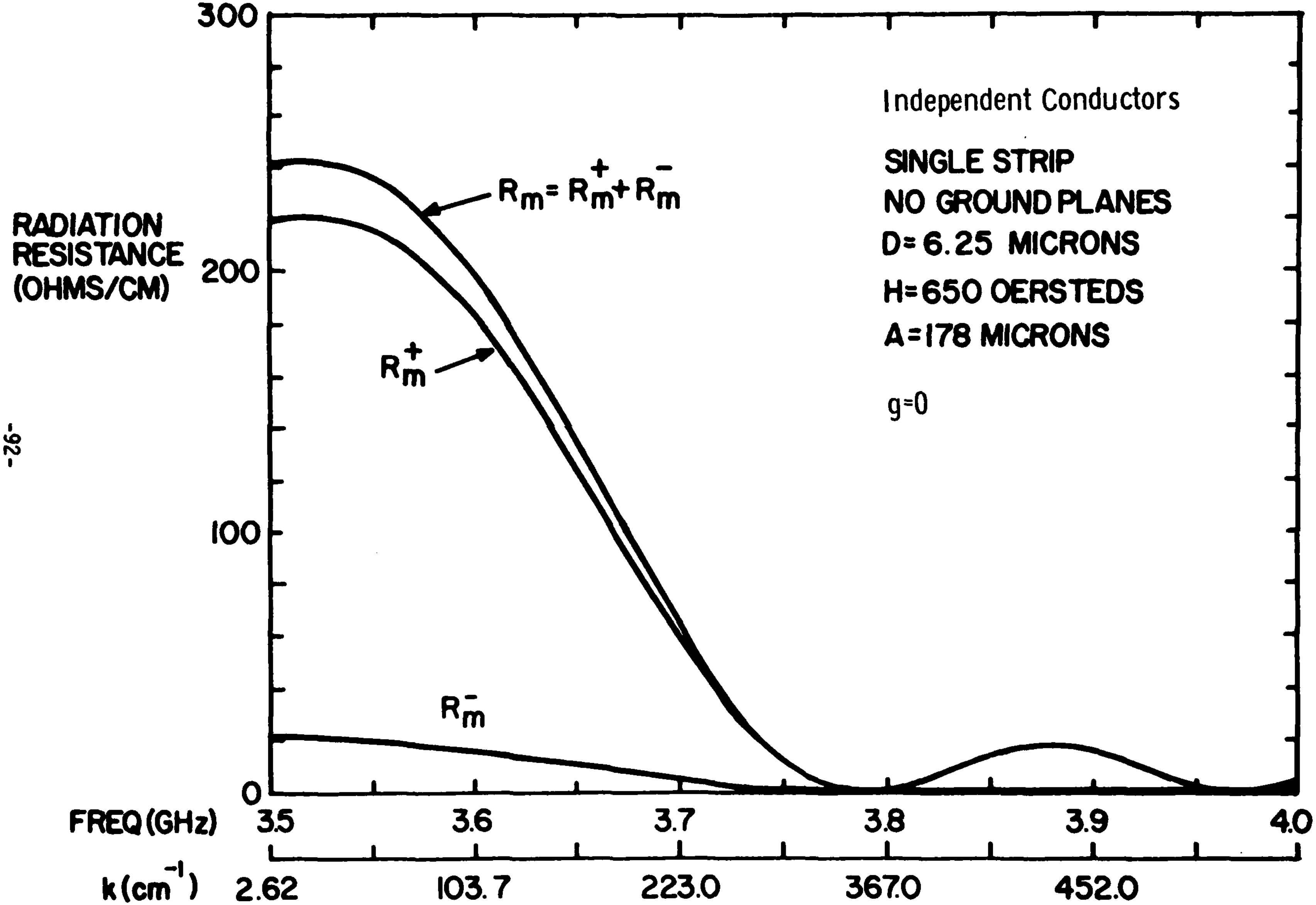

RADIATION RESISTANCE (OHMS/CM)
300
200
100
0
FREQ (GHz)
3.5
3.6
3.7
3.8
3.9
4.0
k(cm^{-1})
2.62
103.7
223.0
367.0
452.0
$R_m = R_m^+ + R_m^-$
R_m^+
R_m^-
Independent Conductors
SINGLE STRIP
NO GROUND PLANES
D=6.25 MICRONS
H=650 OERSTEDS
A=178 MICRONS
g=0

Figure 39

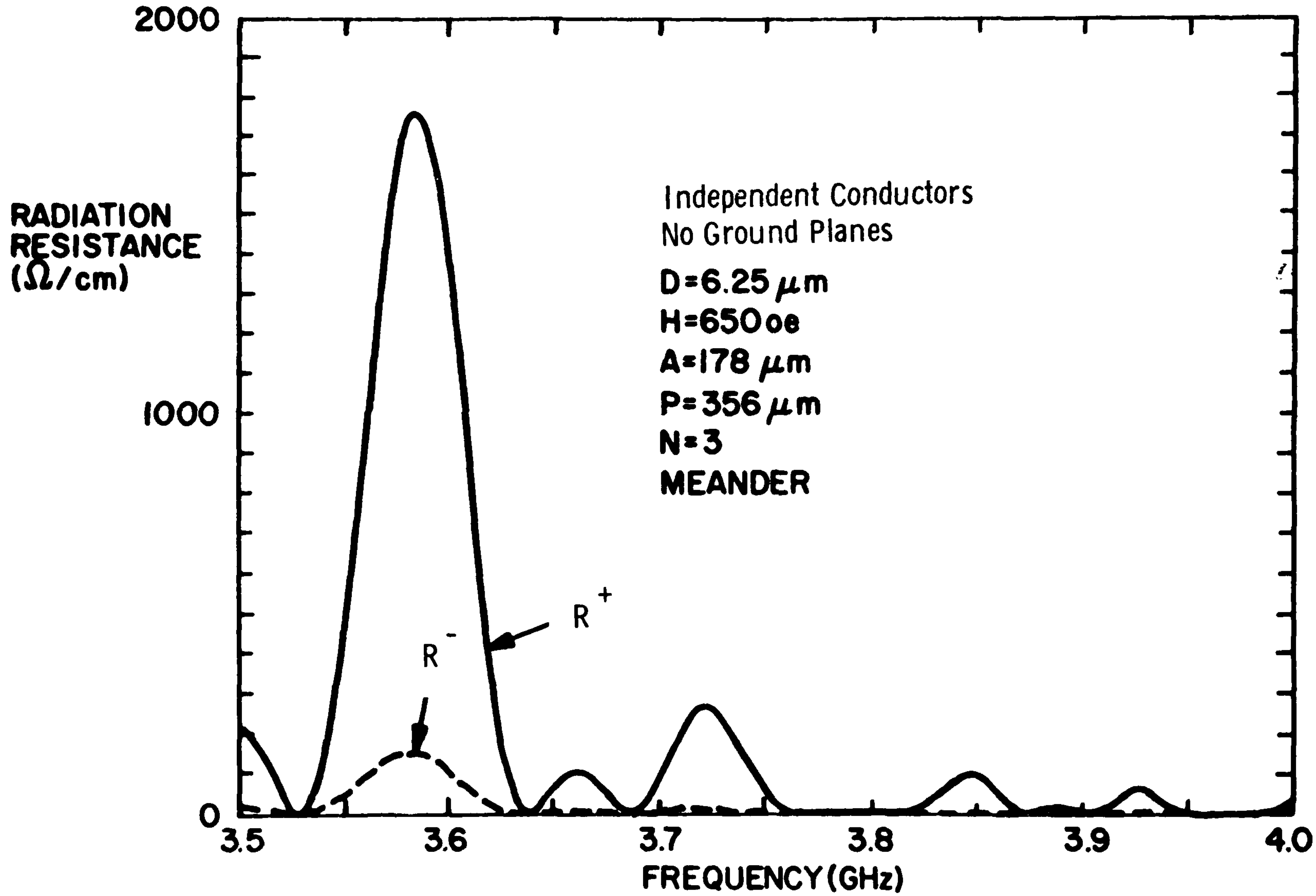

RADIATION RESISTANCE (Ω/cm)
2000
1000
0
Independent Conductors
No Ground Planes
D=6.25 μm
H=650 oe
A=178 μm
P=356 μm
N=3
MEANDER
R+
R-
3.5
3.6
3.7
3.8
3.9
4.0
FREQUENCY (GHz)

Figure 40

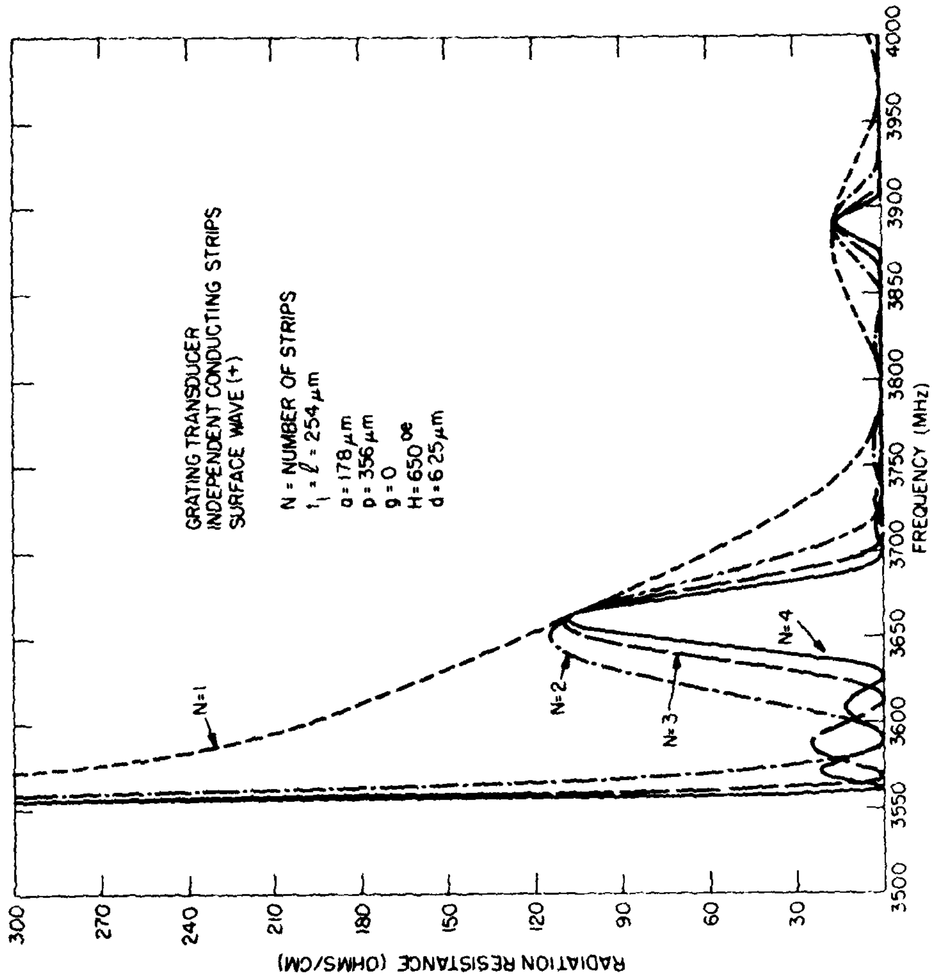

GRATING TRANSDUCER
INDEPENDENT CONDUCTING STRIPS
SURFACE WAVE (+)
N = NUMBER OF STRIPS
a = 178 μm
p = 356 μm
g = 0
H = 650 Oe
d = 625 μm
N=1
N=2
N=3
N=4
RADIATION RESISTANCE (OHMS/CM)
FREQUENCY (MHz)
300
270
240
210
180
150
120
90
60
30
3500
3550
3600
3650
3700
3750
3800
3850
3900
3950
4000

Figure 41

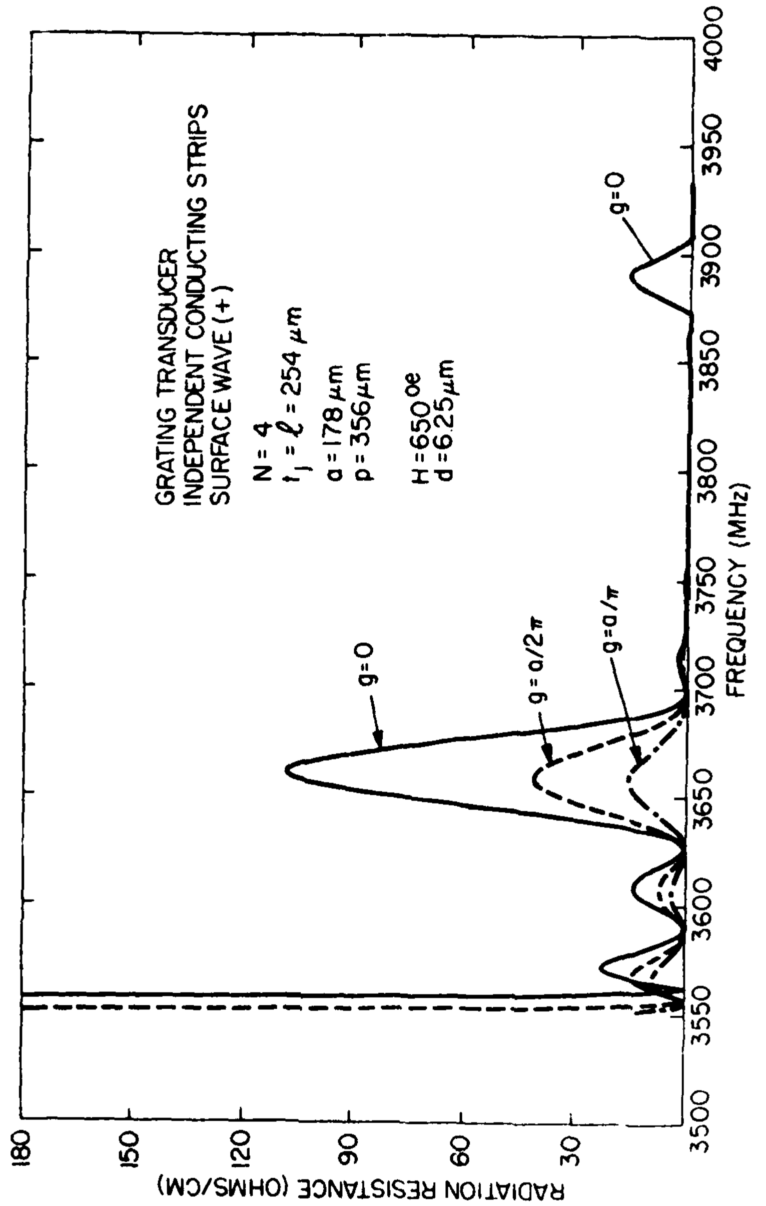

GRATING TRANSDUCER
INDEPENDENT CONDUCTING STRIPS
SURFACE WAVE (+)
N = 4
$t_1 = \ell = 254\,\mu m$
$a = 178\,\mu m$
$p = 356\,\mu m$
$H = 650\,oe$
$d = 6.25\,\mu m$
g=0
g=a/2π
g=a/π
g=0
RADIATION RESISTANCE (OHMS/CM)
180
150
120
90
60
30
3500
3550
3600
3650
3700
3750
3800
3850
3900
3950
4000
FREQUENCY (MHz)

Figure 42

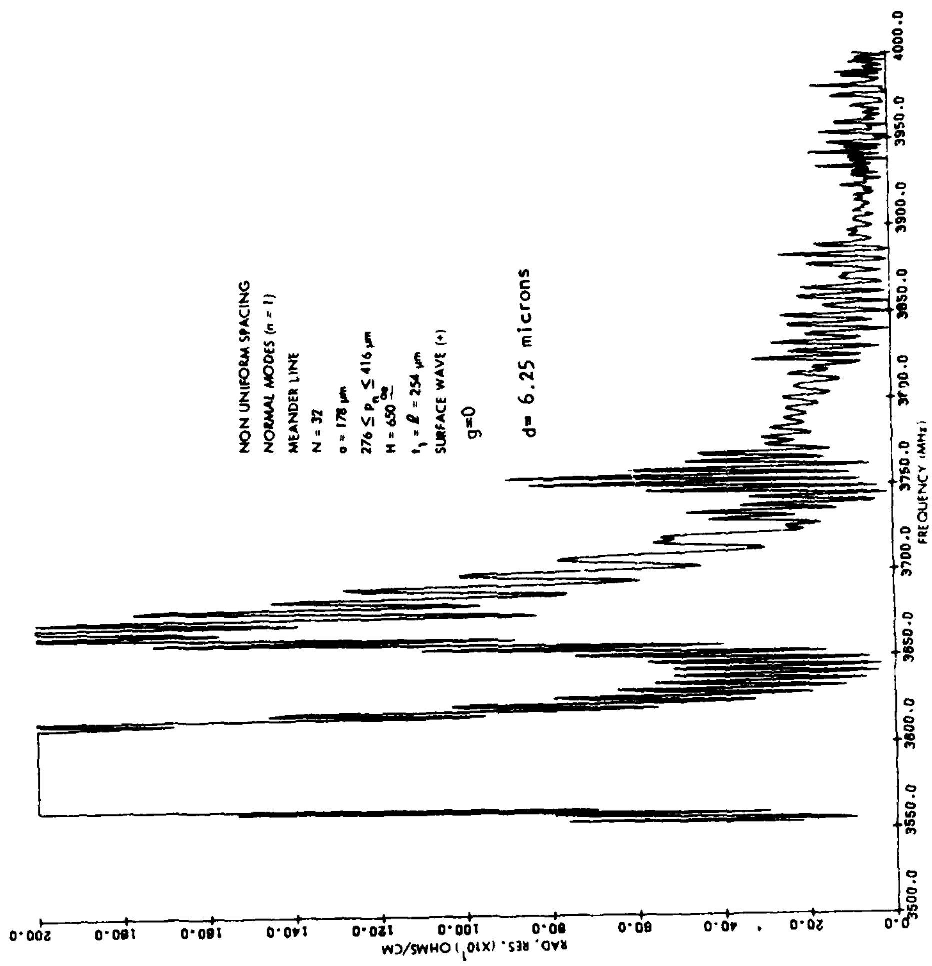

NON UNIFORM SPACING
NORMAL MODES (n = 1)
MEANDER LINE
N = 32
a = 178 μm
276 ≤ p_n ≤ 416 μm
H = 650 $\overset{\circ}{\sim}$
t_1 = ℓ = 254 μm
SURFACE WAVE (+)
g=0
d= 6.25 microns
RAD. RES. (X10^1) OHMS/CM
FREQUENCY (MHz)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
3500.0
3550.0
3600.0
3650.0
3700.0
3750.0
3800.0
3850.0
3900.0
3950.0
4000.0

Figure 43

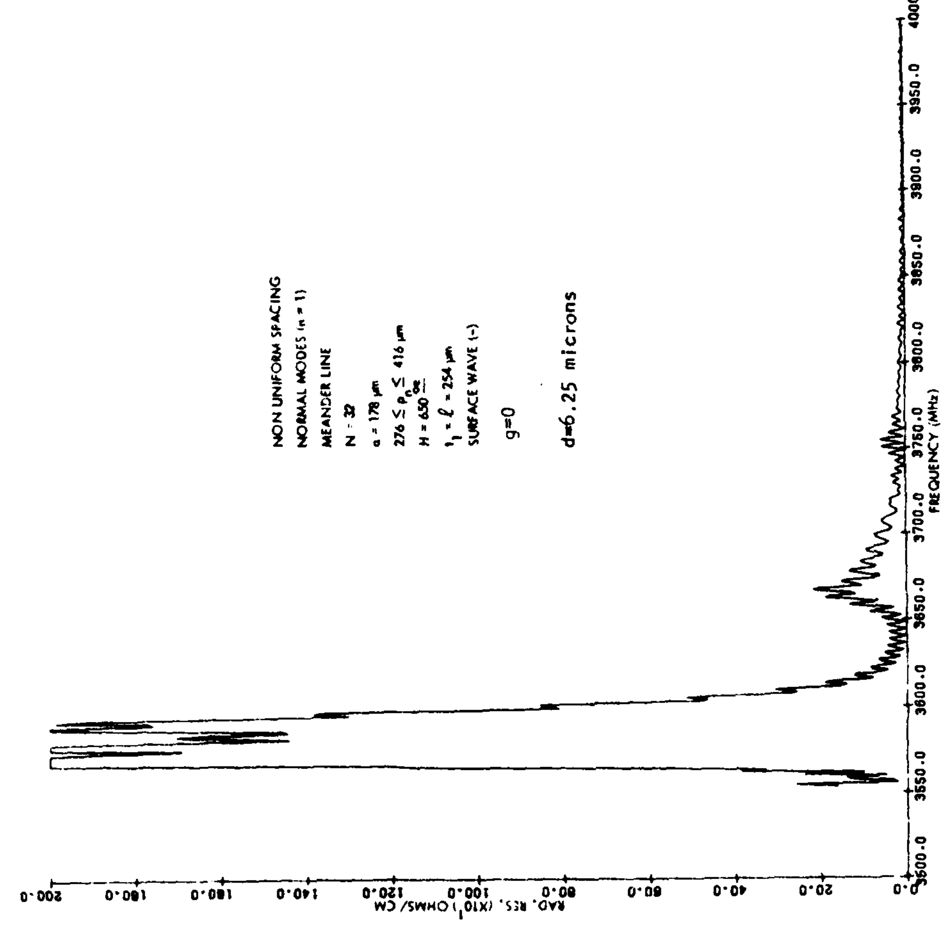

NON UNIFORM SPACING
NORMAL MODES (n = 1)
MEANDER LINE
N = 32
a = 178 μm
SURFACE WAVE (-)
g=0
d=6.25 microns
FREQUENCY (MHz)
RAD. RES. (X10) OHMS/CM

Figure 44

References

1. J.C. Sethares, T. Tsai and I. Koltunov; "Periodic Magnetostatic Surface Wave Transducers"; RADC-TR-78-78; 1978.

2. I.J. Weinberg and J.C. Sethares; "Magnetostatic Wave Transducers With Variable Coupling"; RADC-TR-78-205; 1978.

3. A.K. Ganguly and D.C. Webb; "Microstrip Excitation of Magnetostatic Surface Waves: Theory and Experiment"; IEEE Transactions on Microwave Theory and Techniques; 1975.

4. J.C. Sethares; "Magnetostatic Surface Wave Transducer Design"; IEEE MIT Symposium; 1978.

5. J.H. Collins, J.M. Owens and C.V. Smith, Jr.; "Magnetostatic Wave Signal Processing"; IEEE Ultrasonics Symposium Proceedings; 1977.

6. I.J. Weinberg; "Hilbert Transform by Numerical Integration"; RADC-TR-79-3; 1979.

7. A.K. Ganguly, D.C. Webb and C. Banks; "Complex Radiation Impedance of Microstrip-Excited Magnetostatic Surface Waves"; IEEE Transactions on Microwave Theory and Techniques; 1978.

8. J.C. Sethares and I.J. Weinberg; "Insertion Loss of Apodized Weighted and Non-uniform Magnetostatic Surface Waves Transducers"; Joint MMM-Intermag Conference; 1979.

9. J.M. Owens and C.V. Smith, Jr.; "Interaction of Magnetostatic Waves With Periodic Reflecting Structures"; U. of Texas EMDERL 1979-AFOSR-1; 1979.

10. I.J. Weinberg; "Dispersion Relations for Magnetostatic Waves"; IEEE Ultrasonics Symposium; 1980.

11. H.J. Wu, C.V. Smith, Jr. and J.M. Owens; "Bandpass Filtering and Input Impedance Characterization for Driven Multielement Transducer Pair Delay Line Magnetostatic Wave Devices"; Journal of Applied Physics 50(3); 1979.

12. J.C. Sethares and I.J. Weinberg; "Apodization of Variable Coupling MSSW Transducers"; Journal of Applied Physics 50(3); 1979.

13. J.C. Sethares; "Magnetostatic Surface Wave Transducers"; IEEE Transactions on Microwave Theory and Techniques; 1979.

MISSION
of
Rome Air Development Center

RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence (C^3I) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

Printed by
United States Air Force
Hanscom AFB, Mass. 01731